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MECHANICAL FAILURE PROGNOSIS THROUGH OIL DEBRIS MONITORING

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Exxon Research and Engineering Company

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a study on making optimum use of oil analysis methods for failure prognosis on helicopters. Since the most promising methods have very little statistical history, it was necessary to depend quite heavily on collecting engineering opinions and analyzing them for consensus.

The conclusion reached by this process is that it should be feasible to raise the success of prognosis to a very high level, perhaps approaching 98%,

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without undue expenditure of funds or labor. This would involve two steps:

(1) Provide the organizational maintenance shops with a simple device to measure the fine wear particle content, and authorize them to make preliminary decisions on grounding aircraft.

(2) Provide the aircraft with chip collectors which have more prognostic value, and use these coarse chips as a second channel of information at the shops and laboratories to fill the gaps in the Army Spectrometric Oil Analysis Program.

By making a moderate scale field test discussed in the report, the Army can check the value of this plan and select the optimum hardware from several devices already developed.

PREFACE

This is the final report of the Exxon Research and Engineering Company project entitled "Mechanical Failure Prognosis through Debris Analysis." This study was conducted for the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory under Contract DAAJ02-73-C-0094.

USAAMRDL technical direction was provided by Mr. S. B. Poteate, Jr.

The principal investigator and author of this study was Mr. Alan Beerbower, and program management was provided by Mr. R. R. Bertrand.

Valuable assistance and support were provided by several engineers at SKF Industries, Inc., under the leadership of Dr. L. B. Sibley. Figures 17-40 and explanatory text were supplied by SKF Industries and are their copyright. Reproduction by and for the U.S. Government is authorized.

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1. INTRODUCTION

The ability to detect impending mechanical failure through examination of used lubricating oil is so well established that there is no need to defend the concept. A historic meeting on this subject was held in 1971, and the Minutes (1) show several different systems at work. The present study was designed to examine these and other potential systems, with the objective of raising detection to the level of prognosis. Since these words will be used in very specific senses in this report, they must be clearly understood. In addition the related word diagnosis will be used. The following definitions are essentially those used in medicine:

Detection - the act of laying open what was hidden or concealed

Prognosis - the act of foretelling the course and termination of a disease

Diagnosis - the act of recognizing the presence of disease and deciding as to its character

For example, the same observation of wear particles in engine oil could lead to the following types of statement:

Detection - "This engine is wearing abnormally and should be investigated."

Prognosis - "This engine is wearing in such a way that it will become hazardous to operate between 2 and 25 hours from now."

Diagnosis - "This engine contains a ball bearing which is undergoing fatigue wear."

In the case of helicopters operated by the U.S. Army, the prognosis statement is clearly the most valuable. The detection statement is too vague, while the diagnosis statement is too technical and also lacks the force needed for a recommendation. It must be recognized that there can be no prognosis without detection as a first step. However, prognosis is not necessarily dependent on diagnosis, since an experienced evaluator can see from the trend that a familiar type of case history is developing, even though he is unable to distinguish balls from rollers or fatigue from adhesive wear. Obviously, a certain amount of diagnostic ability would make his job both easier and more precise. One question which this report will address technically, but which will require an economic study to answer, is the point at which diagnosis turns into a useless demonstration of skill.

The structure of the helicopter leads to unique problems and opportunities. Fixed-wing aircraft have been subject to prognosis studies

1 Sawyer, W. T. - Editor, "Minutes of 16th Meeting of the Mechanical Failures Prevention Group," Office of Naval Research, AD 738 855 (1971).

for years, with excellent success, by the U.S. Air Force and a number of major airlines. However, this data proved to be borderline value to this study since most of the engines include gearboxes for accessory power. The helicopter engine contains only bearings, and so provides oil samples free from gear wear. Conversely, the transmissions approach one gear per bearing, and are free from the high temperature zones of the engine. Most helicopters (excluding the CH-47) have tail rotor gearboxes which again are quite unlike any device previously studied for prognosis. It was hoped that the U.S. Navy would have parallel problems, but despite their very willing cooperation, little commonality could be found. Thus, the only .ajor source of relevant data proved to be the Army itself.

Study of the various Army records and reports soon made clear that wear metals were · best source of prognostic information, and that second-best was very pc : in comparison. There was distinct evidence that dirt ingestion was not a major problem to the U.S. Air Force or to Delta Air Lines, while the increased use of silicone rubber seals concealed whatever siliceous material the Army was ingesting. A good many past studies were uncovered (2,3,4) on using the physical and chemical properties of the oil for detection. These were uniformly disappointing. The conclusion was that no alternatives to wear metals were worth considering.

The characteristics of wear metals in the oil offer several possible modes for prognosis. These are discussed in detail in later sections, and are merely listed below:

a - Concentration in the oil
b - Rate of change of concentration
c - Principal and other metals
d - Ratios of metals
e - Chemical form (metal, oxide, metallo-organic)
f - Particle size distribution
g - Particle shape

Also reviewed in later sections are the characteristic surface defects found on teardown. Though these really should be classed as "autopsy," the feedback of such information in clear language to those charged with prognosis is an absolutely vital part of the process.

The tools available for prognosis are then discussed, followed by analysis of the optimum points for evaluation. Finally, recommendations are made which can be implemented immediately.

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2 Anonymous, "Interpretation of Lube Oil Sample Analysis," Electro-Motive Division, General Motors Corp., LaGrange, Ill. (1972).

3 Smith, H. A., "Evaluation of Field and Continuous In-Line Models of Complete Oil Breakdown Rate Analyzer (COBRA)," AFAPL-TR-70-96 (March 1971) AD 884 403.

4 Brun, R., Lamouroux, G. and Schilling, A., "Rapid Methods for the Analysis of Used Oil," distributed by Scholium International, 130-30 31st Avenue, Flushing, N.Y. - 1973.

2. MODES OF WEAR

2.1 General

Two years ago Beerbower (5) prepared a Scientific and Technical Forecast on Boundary Lubrication. This report covered seven models for explaining the phenomena of wear, and wear reduction, under conditions to which elastohydrodynamic theory cannot be applied. Each of the models alone was found to be a mathematical idealization which explained the data over a limited range of velocity, load, temperature and chemistry. In some cases, it was possible to extend the models and close the gaps between; in others, such elaboration appeared unjustified. The modes of wear corresponding to the most successful models are discussed briefly below. As far as is possible, the information is updated to include newer theories which are receiving increased acceptance.

2.2 Sliding Fatigue

This wear model was not at all well accepted in 1972, but was shown in Reference 5 as the leading entry since it explained so much otherwise anomalous data. The theory was started by Bayer (6) as an essentially empirical correlation of observations, and gradually acquired a theoretical basis because of its evident relations, at least in some respects, to rolling fatigue (see 2.3 below). Bayer had recognized two different modes of wear within his model, both of which were characterized by a "zero-wear" period during which some sort of prewear process took place. The milder form, "low transfer" wear, had the longer induction period and corresponds in almost every way to the rolling fatigue model, in which only bulk elastic strain is produced. The other, "high transfer" wear, had a much shorter induction period and seemed to the writer (in 1972) to resemble adhesive wear (see 2.4 below). However, work by Goldblatt (7), Seifert (8) and Suh (9) have all helped to show that wear of this sort also can be related to fatigue. Some additional insight was recently provided by McEvily (10), who emphasized the duality of fatigue processes.

2.2.1 Classical Fatigue was first identified in structural engineering, where it was observed that metal parts subject to cyclic stress below

5 Beerbower, A., "Boundary Lubrication-Scientific and Technical Applications Forecast," Off. Chief of Res. and Dev., Dept. of the Army, 1972 · AD 747 336.

6 Bayer, R. W., et al, "Handbook of Analytical Design for Wear," Plenum Press, New York, 1964.

7 Goldblatt, I. L., "Surface Fatigue Initiated by Fatty Acids," ASLE Trans. 16, 150-159 (1973).

8 Seifert, W. W., and Westcott, V. C., "A Method for the Study of Wear Particles in Lubricating Oil," Wear 21, 27 (1972).

9 Suh, N. P., "The Delamination Theory of Wear," Wear 25, 111-121 (1973).

10 McEvily, A. J., "Failure by Fatigue," Short Abstracts, 20th Meeting of MFPG (May 8, 1974).

the bulk yield value would suddenly break, usually after many millions of cycles. This was traced to the slow growth of microcracks, invisible to the unaided eye, in microplastic regions in the vicinity of stress-raising defects in the material, until the cracks became large enough to be self-propagating and eventually the reduction of area raised the stress to the point of tensile failure (11). This is now known as "high-cycle fatigue." As shown in Figure 1, in this process the number of cycles to failure is very strongly dependent on strain. This relation is described by the Basquin equation, and corresponds to rolling fatigue and to Bayer's "low-transfer" wear.

2.2.2 "Low-Cycle Fatigue" is characteristic of situations in which the yield stress is exceeded enough to produce bulk plastic flow from the start. The relation is described by the Coffin-Manson equation, and corresponds to Bayer's "high transfer" wear. This wear process was originally described by Feng (12). More recently Suh (9) produced a similar analysis, calling the process "delamination wear," while Westcott (13) called it "Beilby layer wear." Suh was able to enhance the model with photomicrographs, by using dead-soft annealed metals for his test pieces. Goldblatt (7) saw this model as a useful explanation for the anomalous behavior of fatty acid additives, and deduced that these caused low-cycle fatigue by lowering the yield stress of the metal. By a minor extension of his theory, it is possible to explain why ester-base lubricants have shorter prefatigue lives than mineral oils, since the ester is a potential source of acid.

It is the writer's opinion that this mode of wear is the most important source of gear metals in used oils. It may also have considerable value in accounting for some kinds of wear in anti-friction bearings.

2.3 Rolling Fatigue

The primary source of rolling fatigue theory is the work of Lundberg and Palmgren (14). Harris (15) later incorporated their model into

11 Chiu, Y. P., et al, "Development of a Mathematical Model for Predicting Life of Rolling Bearings," RADC Technical Report No. 68-54, SKF Report AL68P003 (1968), see section on literature review of structural fatigue failure mechanisms, pp. 43-48.

12 Feng, I-M., "An Analysis of the Effect of Various Factors on Metal Transfer and Wear Between Specimen Pairs of Same Metal and Same Shape, I. The Basic Scheme of Formulation of Metal Transfer and Wear," J. Appl. Phys. 26, 24 (1955). II. "Effect of the Surrounding Atmosphere," J. Appl. Phys. 26, 28 (1955).

13 Westcott, V. C., "Survey of Wear Processes and the Particles Resulting from Wear by Means of a Ferrograph," ONR Contract No. N00014-72-C-0278 (October 1972) AD 753 251.

14 Lundberg, G., and Palmgren, A., "Dynamic Capacity of Rolling Bearings," ACTA Polytechnica, Royal Swedish Academy of Engineering Sciences, 1947 and 1952.

15 Harris, T. A., "Rolling Bearing Analysis," Wiley, New York, 1966.

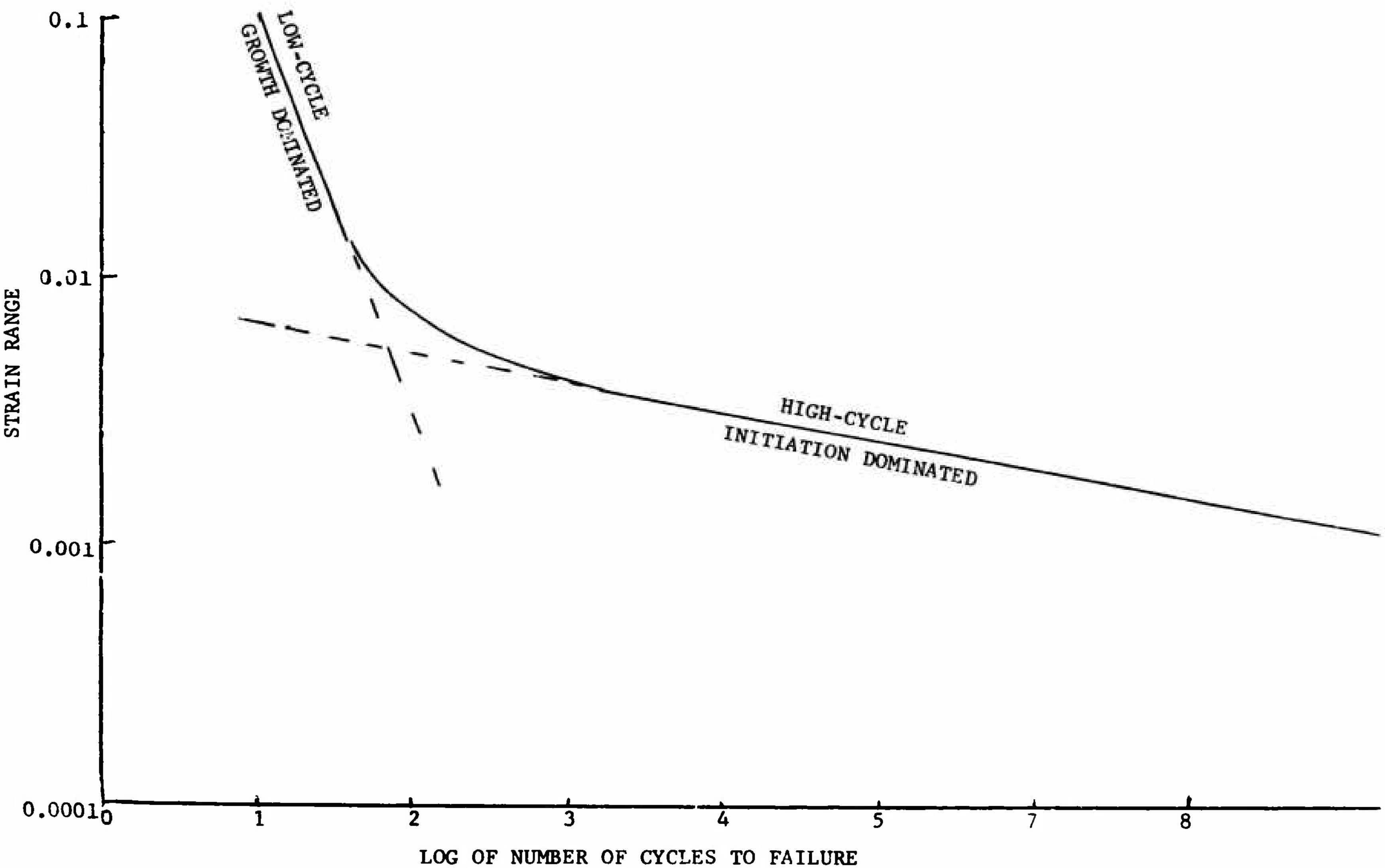

Figure 1. Low-Cycle and High-Cycle Fatigue Modes.

his manual. The main change since then is the advent of vacuum-melted steel, which has shifted the main mode of initiation, thus requiring the development of a rolling fatigue model of broader scope (16,17).

2.3.1 Subsurface Initiation was once the primary cause of ball and roller bearing failure. The problem was that small inclusions of oxide and slag in the air-melted steel served as crack initiators in the regions of highest shear stresses, which occur at significant depths below the bearing contact surfaces. In high-cycle fatigue, it is the time required to initiate the first crack that is important, and the time to propagate to failure is relatively minor. The time to initiate is an inverse function of the number and severity of defects, which depends on their size, shape and location (16). With vacuum-melted steel, all these factors are minimized to the point that the life to 10% failure (L_{10}) at any given load is now from 10 to 100 times that predicted in the Harris manual (15), depending on the degree of freedom from surface defects achieved in any given application.

2.3.2 Surface Initiation was presumed to be the next barrier to making bearings whose life would exceed the useful life of the machine as limited by other factors. Actually, there is reason to believe that this goal has been approached. Rummel (18) showed that "classical spalling" accounted for only 6% of the unscheduled engine removals related to bearings. He defined "classical" as "failures of a subsurface fatigue nature," but since he had no category for surface initiation, this was presumably in the 6%. He added that all of this percentage was due to use of a limited capacity ball bearing in the T63 engine to replace a roller bearing that had given severe skidding damage and roller end wear in service, so that his results can be interpreted as showing no failures due to either subsurface or surface defects.

This rather surprising conclusion has been confirmed by recent work at SKF Industries (19), discussed in the next section.

2.3.3 Particle Initiation is a very new concept which seems to have arisen simultaneously in several laboratories. The writer first heard of it from Hakkenburg of the Caterpillar Tractor Company at the ASLE/ASME

16 Chiu, Y. P., et al, "Refinement and Evaluation of Rolling Bearing Load-Life Model," RADC Technical Report No. 69-265, SKF Report AL69P016 (1969).

17 Chiu, Y. P., Tallian, T. E., and McCool, J. I., "An Engineering Model of Spalling Fatigue Failure in Rolling Contact - The Subsurface Model, the Surface Model, and Engineering Discussion and Illustrative Examples, "Wear 17, 433-480 (1971).

18 Rummel, K. G., and Smith, H. J. M., "Investigation and Analysis of Reliability and Maintainability Problems Associated With Army Aircraft Engines," Vertol Div., The Boeing Co., USAAMRDL-TR-73-28, Eustis Directorate, U.S. Army Air Mobility Res. and Dev. Lab., Ft. Eustis, Va., AD 772 950, August 1973.

19 Dalal, H., et al., "Final Report on Progression of Surface Damage in Rolling Contact Fatigue," ONR Contract No. N00014-73-C-0464 (February 1974) AD 780 453.

Meeting in October, 1973. He pointed out, in discussing a paper by Finkin (20) on abrasive wear, that a hard particle can dent the surface so sharply as to initiate a fatigue crack. Later discussion with Sibley of SKF brought out that this had been noticed, and was visible as a "deformation halo" on the bearing surface around the dent, which upon sectioning shows up as white etching layers in the steel just below the edges of the dents. These steel structural alterations appear to be enriched in carbon compared to the surrounding matrix, due to the temper carbides going back into solution; thus they are identical to the deformation bands around subsurface inclusions, which are initiation points for fatigue cracks (21). Most of these halos stop at 5-10 µm diameter, but some (perhaps 0.1%) propagate so far that they eventually initiate fatigue spalls.

SKF tested this point as part of their Navy contract work (19) and found that the recirculating system which had given normal failures, apparently due to surface defects, suddenly ceased to give fatigue failures when the system was filtered to "super-clean" standards.

2.3.4 Pitch Circle Pitting of gears is a well-recognized form of rolling fatigue. It takes place just where there is no sliding, in agreement with Tallian's (22) observation (in bearings) that plastic flow failure (smearing) due to sliding, and spallation (rolling fatigue) due to rolling were mutually exclusive. Design criteria are given by Wellauer in Dudley's book (23) for limiting the contact stress to prevent this mode of failure, and Rumbarger (24) has derived a more elaborate model for that purpose on an Army contract.

Work at the Naval Air Propulsion Test Center (25) has shown that, at the toothloads used in Army helicopters, pitting is quite unlikely to occur in the scheduled time between overhaul (TBO) intervals.

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20 Finkin, E. G., "Examination of Abrasion Resistance Criteria for Some Ductile Metals," ASME Jour. of Lubr. Tech. 96F, 210-214 and 246 (1974).

21 Leonard, L., "Final Summary Report on Structural Studies of Bearing Steel Undergoing Cyclic Stressing," Office of Naval Research Contract Nonr 4433(00), SKF Report AL70C005 (1970).

22 Tallian, T. E., "On Competing Failure Modes in Rolling Contact," ASLE Trans 10, 418-439 (1967).

23 Dudley, D. W., "Gear Handbook, The Design, Manufacture and Application of Gears," McGraw-Hill Book Co., 1962.

24 Rumbarger, J. H. and Leonard, L., "Derivation of a Fatigue Life Model for Gears," Franklin Institute Research Laboratories, USAAMRDL Technical Report 72-14, Eustis Directorate, U.S. Army Air Mobility R&D Lab., Ft. Eustis, Va., May 1972, AD 744 504.

25 Valori, R., "Evaluation of the Effects of MIL-L-23699 Lubricants on Gear Tooth Pitting in Full Scale Helicopter Transmission Tests (HH-52A) and Correlation with a Small Scale Tester," NAPTC-AED-1923 (January 1970).

Bowen's (26) study for the Army was not so optimistic, as he found a 30% pitting failure rate on the UH-1 sun gear. This was quite surprising, as the Hertz stress he calculated for full takeoff power was only 160 kpsi. According to AGMA Specification 411.02, this should not cause pitting for 10^9 cycles (10^8 with a load distribution factor of 1.21). He felt this anomaly was due to the naivety of the AGMA model, and explained it on the basis of the calculated film thickness. By the Dowson equation, this was only 6 μ-in at the pitch circle.

2.4 Adhesive Wear

This mode was greatly overrated in the past, but is now sinking into perspective. The theory was that wear particles were plucked from one surface by contact with, and adhesion to, the other. This was preventable by reversibly adsorbed additives. When these failed, the result was expected to be hemispherical wear particles.

In Reference 5 this theory was found to be unacceptable on several grounds, except for the extreme case of scuffing wear. The exact nature of the transition from sliding fatigue (Section 2.5) wear to scuffing is still the subject of much experimental and theoretical work. In 1972, there were five models (5), none of which could be completely discarded. Since then, Czichos (27) has added yet another, based on critical combinations of load, velocity and bulk oil temperature. Later he found it necessary to add oil viscosity at a standard temperature, and duration of running, so the original concept of a simplified model is gradually fading away.

2.5 Corrosion and Corrosive Wear

2.5.1 Atmospheric corrosion of nonwearing parts is not usually discussed in conjunction with wear modes. However, it does affect the problems of prognosis because the products often get into the oil and cause high ASOAP readings. The cause is primarily water vapor, which may be trapped in the poorly ventilated gearboxes. Corrosion may be accelerated by salt, and by decomposition products of the ester-base oil MIL-L-23699. The attack is primarily on structural parts made from magnesium alloys. Corrosion of gears and bearings above the at-rest oil level may also take place, though many of the alloy steels used (see Appendix C) are slow to rust.

2.5.2 Corrosion by the lubricant is also a possibility. This takes place below the oil level, on both structural and moving parts. However, the control of "corrosion stability" in MIL-L-23699 is so stringent that only very long TBO aircraft are apt to corrode away appreciable amounts of metal.

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26 Bowen, C. W., Dyson, L. I., and Walker, R. W., "Mode of Failure Investigations of Helicopter Transmissions," Bell Helicopter Co., USAAVLABS Technical Report 70-66, Eustis Directorate, U.S. Army Air Mobility R&D Lab., Fort Eustis, Virginia, January 1971, AD 881 610.

27 Czichos, H., "Failure Modes of Sliding Lubricated Concentrated Contacts," Wear <u>28</u>, 95-101 (1974).

2.5.3 Corrosive wear proper takes place at spots where bare metal has been freshly exposed. The dissolved air in the oil then attacks the metal surface to produce a nonhydrous oxide cap, which eventually breaks off. The reaction rate tends to be high, as the freshly exposed metal is mechanically activated (5). However, the wear rate is limited by the oxygen supply and so does not become catastrophic. A model event is shown in Figure 2.

2.5.4 Reaction of the fresh wear spots with the oil has also been cited as a wear mode (5). As shown below (see 3.4), the Navy has data to indicate this process is a very minor source of metal in the oil.

2.6 Abrasive Wear

It has been general knowledge for centuries that abrasive material in the oil will cause rapid wear, so it is surprising to find how few studies have been made on how this process really works. Perhaps shop experience has led engineers to believe that it is as obvious as the action of a grinding wheel.

Abrasive wear differs from the other modes in that it cannot be self-initiating (5). The process must start with either dirt ingestion, or buildup of wear particles from some other wear mode. However, once abrasion starts in a poorly filtered system, it can become self-accelerating to produce very rapid wear. However, several criteria seem to be very important. First in importance is that the contaminant must be harder than at least one of the surfaces. This is rather unlikely in the engine, where the bearings are $R_c 60$ or harder, unless some bearing metal itself becomes so work-hardened in the course of another wear process as to be dangerous. Ingested dirt appears to be ground up to harmless dimensions and drained out, according to both the Air Force* and Delta Air Lines**. This is in general agreement with ASOAP laboratory practice at ARADMAC,*** where high silicon readings are ignored. Bearing lives at Delta are no shorter than at Northwest or American, where much less ingestion takes place, as shown in Table 1.

Transmissions tend to be similar to engines in that most working surfaces are hard. However, the tail rotor gearboxes are vulnerable, and the bronze control nut on the Acme-threaded adjustment screw is a key point of failure.

The mode of abrasion of most concern in the literature (5) is the "two-body" model shown in Figure 3. The hard particle has embedded in the softer of the working surfaces, and acts as a file. The alternative mode is known as "three-body" abrasion, and has been given a low probability in the past. As shown in Figure 3, the particle can roll along without gouging.

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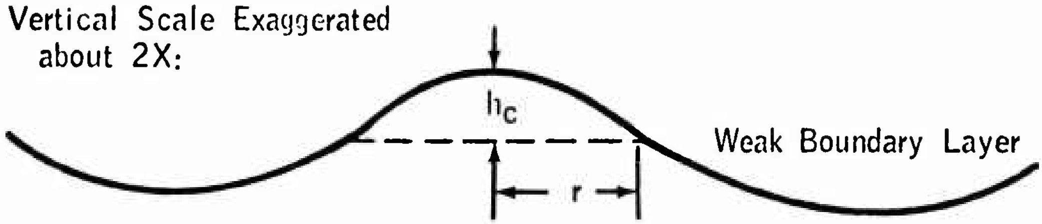
* George, L. P., personal interview at Kelly A.F. Base, Texas,(July 31, 1973).

** Williams, L., personal interview at Delta Air Lines, Atlanta, Ga. (October 19, 1973).

*** Rasberry, A. D., personal interview at ARADMAC, Texas (July 30 and December 3-4, 1973).

Table 1. Airline Bearing Scrappage on JT-8 Engines

Airline	Period	Replacement of Bearings	Bearing Position Number 1	2	3	4	5	6	4-1/2
Delta (727)	6/1/70 to 6/1/72	Rate/1000 hrs	0.0450	0.0289	0.0633	0.0225	0.0364	0.0257	0.0354
		Ave. Time	7545	8147	6528	7662	7074	8620	7637
Northwest (727)	1970/72	Rate/1000 hrs	0.0653	0.0357	0.0620	0.0354	0.1503	0.0742	0.1369
		Ave. Time	7680	7847	4235	6270	4297	4461	4604
American (DC-9)	1970/71	Rate/1000 hrs	0.0263	0.0294	0.0354	0.0118	0.0930	0.0192	0.1064
		Ave. Time	6074	5018	5038	5041	5260	5172	4772



h_c = Critical height for Fe_3O_4 cap

r = Radius of cap

F = Coefficient of friction

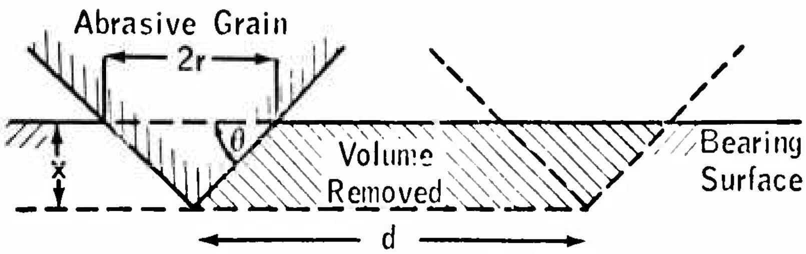
W = Load τ_y = Tensile yield stress of boundary

For an average asperity

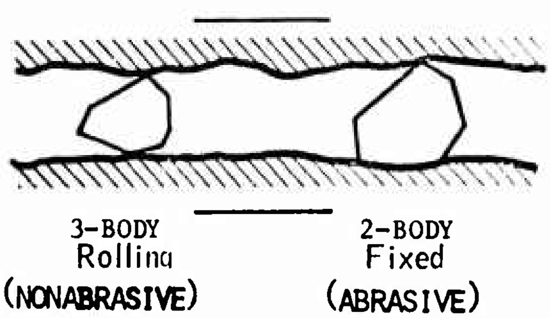
$$h_c FW = \pi r^3 \tau_y N$$

N = Number of asperities involved

Figure 2. Torque Balance for Removal of an Oxide Cap (Corrosive Wear).



A - Abrasive Wear Model in Which a Cone Removes Material from a Surface



B - Sketch of Abrasive Particles Between Rubbing Surfaces

Figure 3. Two-Body Abrasive Wear.

However, in view of the new ideas discussed in 2.3.3 above, this rating must be reconsidered.

2.7 Other Wear Modes

Three other wear modes are known, but were not found to be very active in Army helicopters. In order to clarify exactly what is being excluded, these are described briefly.

2.7.1 Fretting is the process in which one metal surface rides on another in a reciprocating mode of low amplitude and moderate frequency. The product is fine metal powder; if the powder is partly or fully oxidized, the process is known as "fretting corrosion." Some Army reports indicate that fretting was found on teardown, but the actual failure mode may have been creeping or spinning of the bearing ring (see Appendix B), which usually begins as fretting wear of the ring mounting surfaces resulting in loss of the original design fit.

2.7.2 Cavitation is a form of erosion found at the inlet ports of some oil pumps operating at too low suction pressure. It has never been clearly established as a wear mode.

2.7.3 Electrical Arcing is almost always mentioned in bearing damage analysis manuals, because of the possibility that it will not be considered. However, the fairly heavy current required is not apt to arise in Army helicopters, and such damage has not been reported.

2.8 Dominant Wear Modes in Engines

To put the above catalog of wear modes into perspective, it is necessary to go through the list again for each major item. The engine is relatively simple, since all the wear is in the bearings. (Foreign object damage is not within the scope of this study.) The statistics of frequency are derived from Rummel's (18) index of severity, and are summarized in Table 2.

Table 2. Relative Frequency of Wear Modes in Engines

Category	Frequency (%)
Low-Cycle Sliding Fatigue	54
Rolling Fatigue	11
Abrasive Wear	4
Insufficient Flow	12
Race Rotation and Displacement	16
Miscellaneous	3
	100

2.8.1 Sliding Fatigue Wear includes the following categories:

Nonclassical Spalling due to Excessive Loads	25%
Nonclassical Spalling due to Manufacturing Errors	8
Cage Wear and/or Cracking	13
Roller Skidding Damage	8
	54%

Thus, 54% of the total engine bearing problems can be attributed to this mode.

The shape of the curve in Figure 4 is based on the Bayer (6) high transfer wear model for a ball sliding on a flat surface. For machine elements approaching flat-on-flat geometry, the line tends to become straight. It is arbitrarily placed in vertical relation to the other curves.

2.8.2 Rolling Fatigue is considered equivalent to Rummel's Classical Spalling and accounts for 11% of his total. The shape of this curve in Figure 4 is based on estimates of the propagation rate of spalls (28) initiated as described by Harris (15), with the assumption that no defects are so deep as to cause ball splitting.

2.8.3 Abrasive Wear is taken from Rummel's Inadequate Filtration. Since he did not separate this from Insufficient Flow, the value used was 25% of his total for Nonclassical Spalling due to Inadequate Lubrication. By this criterion, abrasion accounts for 4% of his total.

The curve in Figure 4 is based on the Beerbower (1,5) model, in which wear rate is proportional to the accumulated debris. As before, the vertical placement relation to the other curves is arbitrary.

2.8.4 Other Failure Modes include Insufficient Flow (12%), Race Rotation and Displacement (16%) and Miscellaneous (3%). While all these produce wear debris and so are legitimate goals for prognosis, they are not subject to mathematical modeling and so are not plotted in Figure 4.

2.9 Dominant Wear Modes in Transmissions

The transmission on a helicopter is subject to almost every known mode of wear. The bearings have all the same problems as those in engines. The gears have problems of a nature so different from those of bearings that they cannot even be discussed in the same words (Appendix A). The modes in which they wear under various loads are illustrated in Table 3. In addition, there are strong interactions in both directions. Wear debris from the gears tends to pass directly into the bearings before filtration is possible. Conversely, any wear of the bearings tends to let the gears skew, with dramatic increase in the loading stress.

There are two excellent analyses of transmission failures. Bowen (26) covers the UH-1 and CH-47 failures during five months in 1970.

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28 Littmann, W. E., et al, "The role of Lubrication in Propagation of Contact Fatigue Cracks," Trans. ASME, Jour. Lubr. Tech. 90, 89-100 (1968).

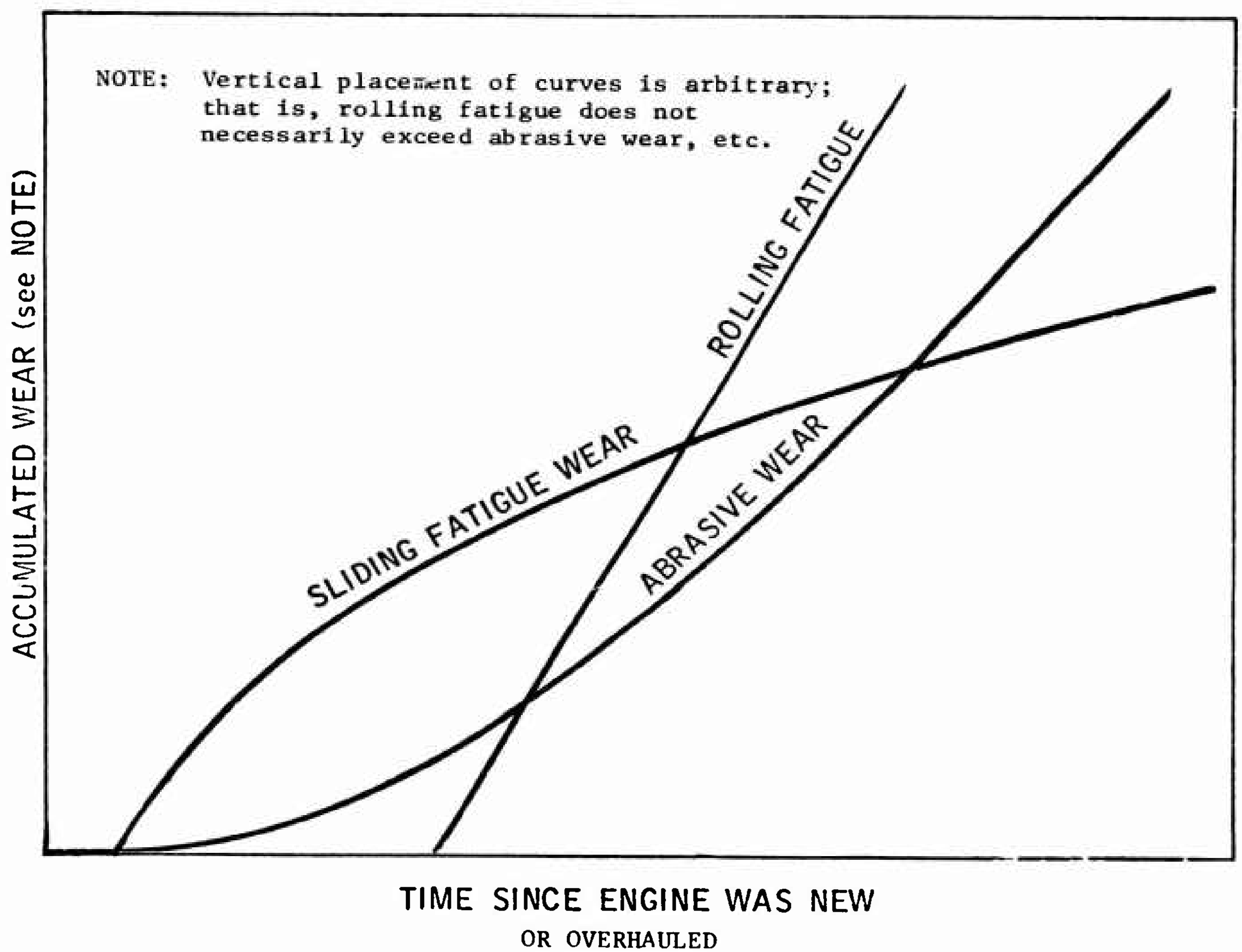

Figure 4. Shapes of Curves for Wear Modes in Engines.

Table 3. Gear Damage Modes

	Design Load	Heavy Load	Very Heavy Load	Destructive Load
Short-Term Damage	None visible	Scuff[1] at tips	Scuff[1] on 50%	Galling
Wear Particles	<1 μm	Log square	Log square	~300 μm
Long-term Damage	Fatigue at pitch circle	Rippling	Scoring[2]	Burnt
Wear Particles	Log square	~125 μm swarf[3]	Log square	--

[1]Roughened in a mottled pattern.

[2]Radial grooves on teeth.

[3]Beilby layer extruded past tooth tip and broken off.

Dougherty (29) covers the CH-46 and CH-47, some H-3 data from Sikorsky, and the Bowen (26) data on the UH-1. To assess the relative importance of wear modes in bearings and gears, Bowen's Table III on the UH-1, and Dougherty's Table XI on the CH-47, were recomputed into the pattern used on the engines in 2.8, in Table 4.

One serious difficulty encountered was that Bowen lumped together "corrosion and debris" as a failure mode in many cases. These were arbitrarily divided into halves; one half was charged to "corrosion" and the other to "abrasion." A related problem is that Bowen used the glossary established in his report and modified slightly as Appendix A, while Dougherty used the Vertol damage report code. These are not compatible, and both were undoubtedly further distorted by force-fitting into the wear modes shown in Table 4. The Bowen and Dougherty tables are shown in Appendix B. In a recent interview, Bowen advised that there is a great deal of unanalyzed data stored on a magnetic disk at the Bell Engineering Computing Section, which is the property of AAMRDL.

Table 4. Relative Frequency of Wear Modes in UH-1 and CH-47 Transmissions

Wear Mode	UH-1		CH-47	
	Bearings	Gears	Bearings	Gears
Sliding Fatigue (1)	0	19.01	5.97	8.24
Rolling Fatigue (2)	14.12	1.95	29.08	0
Adhesive	0	11.72	4.55	4.82
Corrosion	20.99	2.48	25.80	9.46
Abrasion	22.19	3.27	2.74	0.64
Fretting	4.27	0	1.89	6.81
Total	61.57	38.43	70.03	29.97

(1) Low Cycle
(2) High Cycle

2.9.1 Sliding Fatigue Wear in the UH-1 appears to be limited to gears, but probably the bearings also shared in this mode. If so, the information was not readily retrieved.

2.9.2 Rolling Fatigue Wear appears higher for these bearings than those in the engines. This would again indicate that the communication problems led to a difference in classification. However, if we consider

29 Dougherty, J. J. III, and Blewitt, S. J., "Analysis of Criteria for On-Condition Maintenance for Helicopter Transmissions," Boeing Vertol Co., USAAMRDL Technical Report 73-58, Eustis Directorate, U.S. Army Air Mobility R&D Lab., Ft. Eustis, Va., September 1973, AD 773 024.

"Total Fatigue Wear," the transmission still shows far lower values than the engine. The important point is that the transmissions are vulnerable to other modes, rather than having some special resistance to fatigue.

2.9.3 Adhesive Wear did not appear at all in the engine, or in the UH-1 transmission bearings, but was applicable in the CH-47 transmission bearings. The gears in both transmissions showed adhesive wear. That in the UH-1 was not considered highly significant by Bowen during his study, since he felt that it was due entirely to misalignment resulting from bearing wear, a secondary process. A line for this mode is shown in Figure 5.

2.9.4 Corrosion was not observed in the engine, but is a major factor in the transmission bearings. The agreement between the UH-1 and CH-47 is probably better than it should be, due to the data handling. As anticipated, the gears are less subject to this form of damage than the bearings. A straight line for this mode is shown in Figure 5.

2.9.5 Abrasive Wear shows up high in the UH-1 bearings; this may be partly due to the arbitrary separation of "corrosion and debris" noted above, but probably also represents a real problem. The other abrasion values are comparable to Rummel's 4% in the engine.

2.9.6 Fretting appears as a rather consistent item. As noted above, there is probably a tendency to report more fretting than actually corresponds to the definition in Appendix A, but both authors seem to have taken pains to avoid this problem.

2.10 Dominant Wear Modes in Gearboxes

Unfortunately no similar compilation of data was available on gearboxes, and efforts to compile one were fruitless. The general pattern appears to be similar to that in transmissions, with a few exceptions.

2.10.1 Lack of Filtration, combined with the small volume, appears to lead to high recycle of wear particles. This may be assumed to add to the abrasion problem, especially the "two-body" mode already noted, which involves the bronze control nut.

2.10.2 Outside Contamination has additional significance in the 90° UH-1 tail rotor box, according to personnel at Fort Campbell. Overgreasing the hub bearing forces grease and wear debris down the shaft housing into the gearbox, with serious effects.

2.10.3 Water has been reported as a serious cause of false alarms in the gearbox, since it produces the same electrical effect as a chip. This fact, plus the many ASOAP reports of 40 ppm or more of magnesium in the oil, lead to the conclusion that the gearbox is exceptionally prone to corrosion.

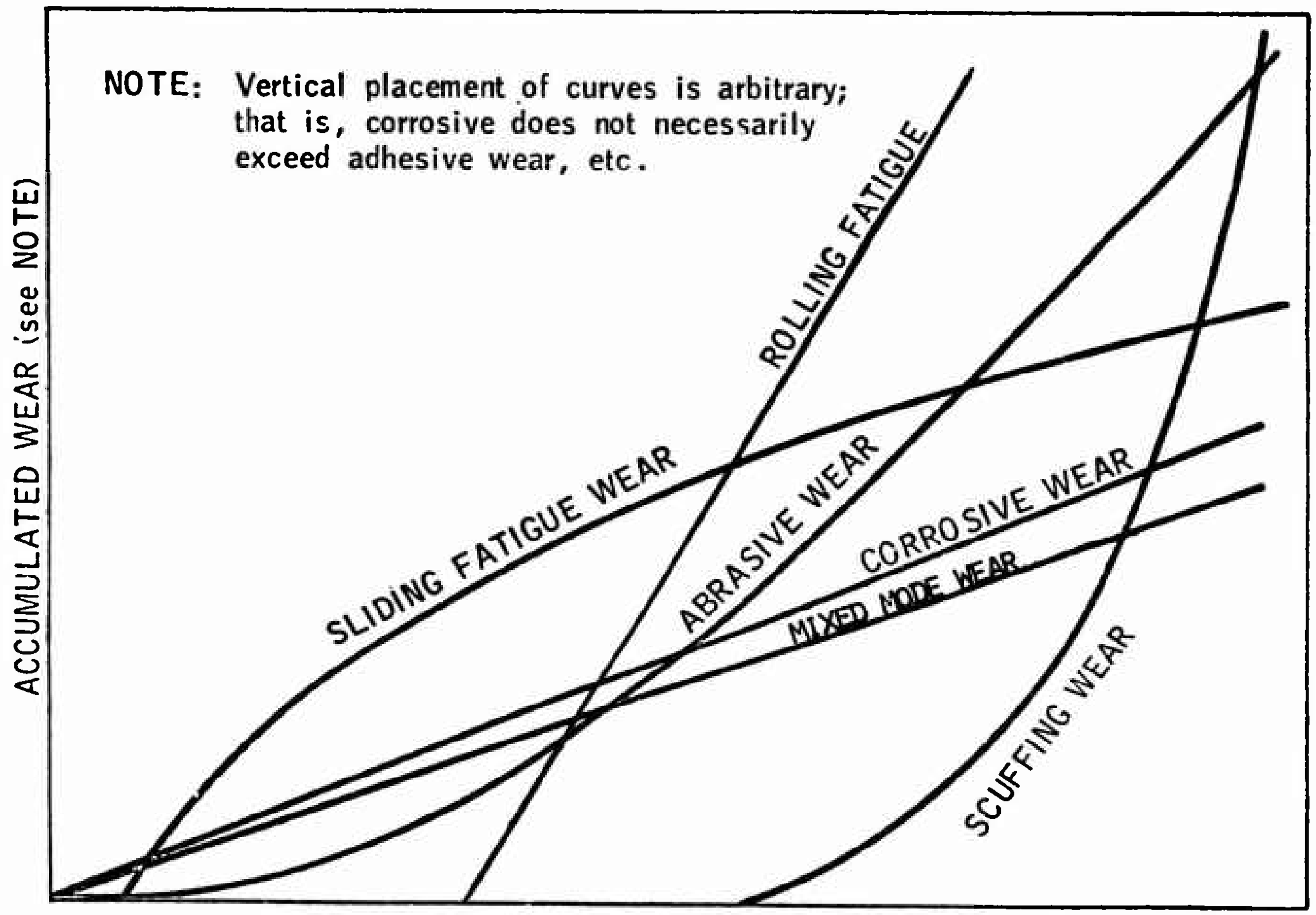

Figure 5. Shapes of Curves for Wear Modes in Transmissions.

3. PARTICLES FOUND IN OIL

For the present purposes, the most important aspects of the wear process are the effects on particle population. There are several such effects, which differ greatly in their value for prognosis. The measurable parameters include:

- Sizes of particles
- Number of particles of each size
- Shape of particles
- Chemical composition
- Rates of change of these variables

In some modes of examination, two or more of these parameters may be lumped together. For example, ASOAP combines the size, number and composition

Other parameters are hidden and may be deduced from the measurements. These include:

- Primary source of particles
- Secondary wear modes
- Secondary damage to particles

All the above aspects relate to the growth and nature of the particle population. Opposing forces also exist, and may be highly selective:

- Settling of particles
- Filtration
- Magnetic plug collection
- Adhesion to component walls

The following discussion is based on particle sources, working backwards to the measured parameters. Unfortunately, direct examination of wear particles in lubricating oil is such a recent development that it is necessary to draw on related fields of engineering for some details. In addition to the wear modes of Section 2, the following are important:

- Particle studies in hydraulic systems
- Particles found in fuels and propellants
- Grinding of metallurgical powders and pigments

3.1 Sliding Fatigue Particles

As mentioned in 2.2, Bayer (6) identified two kinds of wear which seem to correspond to the two kinds of fatigue. They also generate two kinds of particles.

3.1.1 High-Cycle Sliding Fatigue is characterized by failures which appear to be individual grains popped out of the surface. These have been identified by Trans-Sonics (13) and an example is shown in Figure 6.

Figure 6. High-Cycle Sliding Fatigue Particles.

3.1.2 Low-Cycle Sliding Fatigue has come up so recently that less detail work has been done on the particles than on those from other modes. An example of the particle size distribution is shown in Figure 7, in comparison with particles from scuffing wear (3.3). Particles from these wear modes were examined by Trans-Sonics, and their shapes are shown in Figure 8. These particles were made in a ball-on-cylinder simulator which is known to correlate with the Ryder Gear Tester, and so may be presumed typical of these gear wear modes until further studies can be made. These flakes correspond to both the "transfer" (12) and "delamination" (9) theories.

3.2 Rolling Fatigue Particles

As in sliding fatigue, rolling fatigue appears to be divisible into high- and low-cycle modes, though the former has received almost all the research.

3.2.1 High-Cycle Rolling Fatigue occurs in gears at the pitch circle and this has been the subject of a number of studies. Unfortunately, most of these are unpublished. However, none of them seem to have included wear particle examination. Of those released, the studies at Trans-Sonics (13) sponsored by the Office of Naval Research, have shown some particles of a peculiar blocky shape. They look very much like grains that have fallen out of a surface. The pits found at the pitch circle have a similar geometry, and it may be presumed that there is a causal relationship.

A report by the Naval Air Propulsion Test Center (25) indicates that pitch circle fatigue takes a long time or a serious overload, so it is probable that Army helicopters are not prone to this form of damage.

There have been very extensive studies at SKF Industries, both under company and Navy sponsorship, on rolling fatigue in bearings. However, these only recently began to include studies of the particles. The SKF engineers do not feel they can make any definitive statement on particle shape as a tool for prognosis or diagnosis. However, they do feel that there is a demonstrated need for more work in this area.

3.2.2 Low-Cycle Rolling Fatigue has received very little study under that name, but appears to be associated with a phenomenon known as "surface distress" (see 4.2.2). No statement can be made as to shape with any certainty, but analogy would tend to predict the flaky shape. On the other hand, Trans-Sonics (13) feels their observation of spherical particles can be related to rolling fatigue. An example is shown in Figure 9. Scott (30) observed the same spheres under heavy loads, so they may arise from this mode (31).

3.3 Particles from Adhesive Wear

As discussed in Section 2.4, it has become evident that adhesive wear is not a very common event. However, when it does occur the results

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30 Scott, D., and Mills, G. H., "A Scanning Electron Microscope Study of Fracture Phenomena Associated with Rolling Contact Surface Fatigue Failure," Wear 16, 235-237 (1970).

31 Loy, B., and McCallum, R., "Mode of Formation of Spherical Particles in Rolling Contact Fatigue," Wear 24, 219-28 (1973).

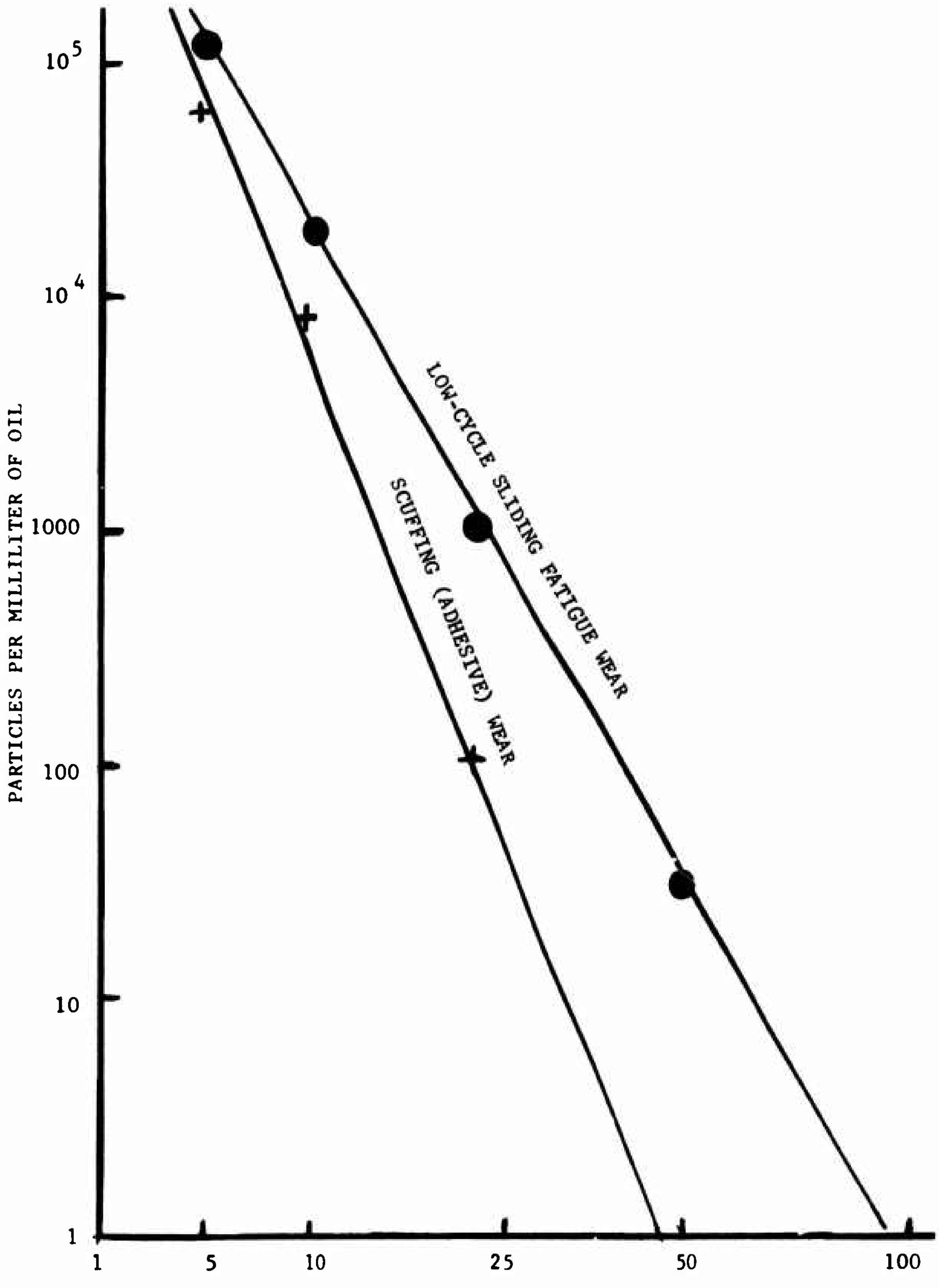


Figure 7. Size Distributions of Wear Particles.

Figure 8. Low-Cycle Sliding Fatigue Particles.

SEM at 2000 X

Figure 9. Spherical Particles from Rolling Fatigue (36).

are so destructive that prognosis of this mode is important out of all proportion to frequency.

Pitting and galling of gears is characterized by massive transfer of metal without producing much debris fine enough to be called particles. Instead, this mode results in large chips which appear in the filters and chip detectors, or are lost in dead spots.

Scuffing of gears is not an important primary failure mode in the UH-1 or CH-47 according to Bowen (26), who found only secondary damage due to loss of alignment through bearing or spacer wear. This can be attributed partly to good design, and even more to good quality control in the procurement of vacuum-melted steel gears and oils of certified Ryder Gear Tester performance. A recent NASA-sponsored study on microfog lubrication (32) included comparison of the Ryder gears (designed about 1944) with modern gears designed with the help of Sikorsky. The latter did not scuff at all under conditions giving up to 22% on the old Ryder design.

If scuffing does take place, the primary particle is a large flake which may be seen glittering in the oil as it settles with a tumbling motion. Presumably most of these are removed by filtration, magnetic plug or settling before much secondary damage takes place. Examples are shown in Figure 10.

Bearing wear is even less prone to produce adhesive wear particles. The phrase "pitting and galling" is not associated with damage to ball bearings, and what is called "smearing" or "galling" in roller bearings does not really correspond to gear galling. There is a mode known as "gross smearing" in which metal is transferred in tightly adhering patches. As in gears, this mode does not produce much fine debris, but only large chips.

Micro-smearing or skid damage is the bearing equivalent of gear scuffing. The resulting particles have not been clearly identified but may be presumed to be small flakes, based on the "granular" appearance of skid damaged surfaces (see Section 4.3).

3.4 Corrosion and Corrosive Wear Particles

The phenomena of corrosion and corrosive wear are clearly distinct, and so are the primary particles.

3.4.1 Corrosion of nonrubbing parts results in hydrous oxide films which grow thick enough to spall off in gross sheets. However, due to the low density and extreme brittleness of these hydrous oxides, they tend to be reduced by secondary processes to fine dust (less than 1 μm).

3.4.2 Corrosion by the lubricants has often been cited as a source of soluble, or at least colloidal, metal in the oil. Klaus (33) has shown that

32 Beerbower, A., and Overhoff, R. F., "Microfog Lubrication of Helicopter Gearing," NASA Contract NAS-3-16825 (1974).

33 Klaus, E. E., and Tewksbury, E. J., "Microcorrosion Studies with Functional Fluids," Lubr. Eng. 29, 205-211 (1973).

20 μm

Figure 10. Particles from Scuffing Wear.

when metals dissolve in oil, the concentration passes through a peak and then falls rapidly to near zero. The metal has dropped out in the form of deposits on the walls and sludge. If metal continues to dissolve, it is promptly deposited and only a very low equilibrium concentration is retained in the oil.

Recent work by the Navy at Pensacola (34) confirms this. Used MIL-L-23699 samples were filtered through an 0.65 µm membrane, and from 95 to 100% of the iron, silver, chromium, magnesium and lead were removed. However, only 75% of the copper and very little of the tin were removed, so there are exceptions to this "rule." Another was found at ARADMAC, when a sample with a suspiciously high magnesium content was subjected to a particle count. The number of particles greater than 5 µm was equivalent to that found in new oils.

3.4.3 True corrosive wear is not a very common cause for rapid damage in oil-wetted systems (5). Corrosive wear is a microprocess, resulting in small discs or caps of magnetic iron oxide. Probably the primary particle is about 5 µm in diameter and half that thickness. Pursuit of the distinction from static corrosion does not appear justified. If it should be, the ASOAP method provides a means for chemical diagnosis, since the corrosion particle will tend to be magnesium or aluminum. Hydrous iron oxide (FeO·OH) would indicate static corrosion of steel parts. However, magnetic iron oxide (Fe_3O_4) would indicate corrosive wear unless clearly traceable to some high-temperature manufacturing process. Such particles are shown in Figure 11.

In any case, the presence of corrosion products has little value for prognosis. Instead, it has been recognized as a handicap in the ASOAP method, since it results in a high "background" or "noise" level that tends to mask more meaningful signals.

3.5 Abrasive Wear Particles

Only the two-body abrasion model in Figure 2 need be considered, since the three-body model apparently leads to the same particles as made by sliding fatigue. One sort of particle expected from two-body wear was found by Seifert (8) and Westcott (13). These are cuttings, looking very much like miniature lathe chips, or flat wire wound into spirals and helices (Figure 12). These are fairly scarce compared to the flat particle background, as are all special shapes.

Another sort of particle has been predicted by Antler (35), on the basis of laboratory experiments on gold surfaces. This is the "prow particle," a peculiarly crushed lump with one flat side, which forms on the front of the abrasive grain. Not all metals are capable of this mode of

34 Bond, B. B., "Effect of Sample Filtration on Sample Analysis," Navy Oil Analysis Program TR 9-73 (May 1974).

35 Antler, M., "Stages in the Wear of a Prow-Forming Metal," ASLE Trans 13, 79-86 (1970).

10 μm

Figure 11. Particles from Corrosive Wear (13).

15 μm

Figure 12. Particles from Abrasive Cutting Wear (13).

wear, which may explain why these particles have not been very conspicuous. However, Ruff (36) may well have caught one in Figure 13.

3.6 Fretting and Fretting Corrosion Particles

The fretting mode produces particles in the smallest size range, due to the small amplitude of motion. When metallic, the dust may even look black. Fretting corrosion produces red dust, like ferric oxide pigment. There have been no reports on shape, but the relation to adhesive and corrosive wear leads to the expectation of the familiar irregular flakes.

3.7 Ingested Particles

The aircraft turbine engine has a strong tendency to suck in dust, and the Army helicopter has unlimited opportunity to do so. Most of the dust passes through the engine, but some tends to centrifuge out in the compressor. This has not been any problem in the T63, but in the JT-8* and the T53 (37) it finds its way through the labyrinth seals into the bearings.

The nature of airborne dust has been studied in great detail. The particle shapes are irregular, but the size distribution shows an important regularity. This is discussed in Section 3.9.

3.8 Particle Fracture Processes

The counting and sizing of particles, and attempting to relate the results to the process which generated them, has been an active science for many years. This activity is not widely known to mechanical engineers, since the two main groups involved are the mining engineers and the industrial hygienists. The former are the more informative, since they can study both the process and the product. Their results are well summarized by Orr (38).

Three processes are recognized as operating in size reduction. These are impact, abrasive and chipping fracture.

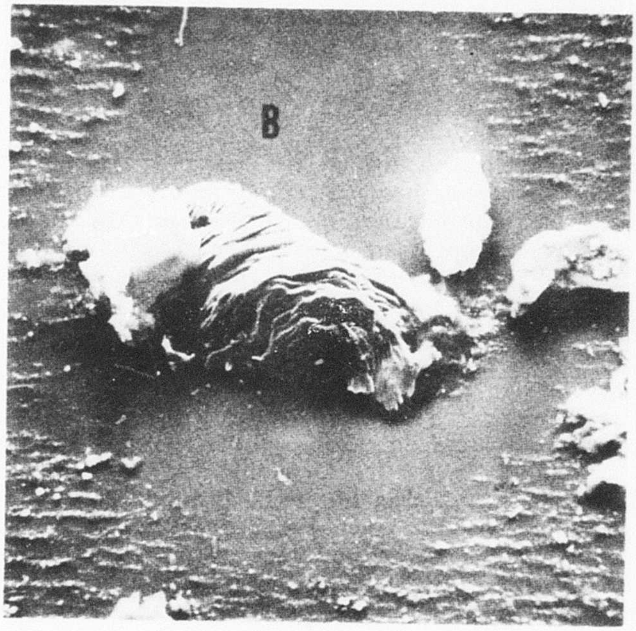
3.8.1 Impact Fracture takes place when a force of sufficient magnitude is applied normal to the parent body, which then splits symmetrically into at least two, and generally many, particles. This does not correspond to any wear mode, but is relevant to the fate of primary particles. The theoretical equation is

* L. Williams, Delta Air Lines, October 13, 1973.

36 Ruff, A. W., "Metallurgical Analysis of Wear Particles and Wearing Surfaces," NBSIR 74-474, AD 778 340.

37 Lynch, C. W., and Cooper, R. B., "The Development of a Three-Micron Absolute Main Oil Filter for the T53 Gas Turbine," ASME Jour. of Lubr. Tech., 93F, 430-436 (1971).

38 Orr, C. Jr., "Size Reduction," Encyclopedia of Chem. Tech. 18, 327-338, Interscience Div., John Wiley and Sons, New York, 1969.



SEM at 500 X

Figure 13. Prow Particle from Abrasive Plowing Wear (36).

$$N = [1 - (X/X_0)]^r$$

where N is the cumulative weight fraction coarser than dimension X, X_0 is the dimension of the parent body, and r is a measure of the number of breaks. The shape of the characteristic curve is shown in Figure 14.

3.8.2 Abrasive Fracture takes place when the force is applied parallel to the surface of the parent body. This corresponds very closely to two-body abrasion in Figure 3. There is no theoretical equation, since the dimensions of the particle are so dependent on the prevailing geometry, but the result is always particles of essentially uniform dimension. This is also shown in Figure 14.

3.8.3 Chipping Fracture is akin to both coarse abrasion and incomplete impact fracture. Again, there is no theoretical equation because of dependence on local geometry which cannot be predicted. However, the pattern of particles produced is well enough known to be plotted in Figure 14 with considerable confidence. This fracture mode is visualized as being characteristic of fatigue and adhesive wear.

3.8.4 Summation-of-Events Fracture is a term for any complex process in which there may be more than one mode. It is generally assumed that, in a grinding device, the three basic modes operate so that the relative breakage rates are constant relative to one another. Under these conditions, the data are often well represented by the Rosin-Rammler distribution:

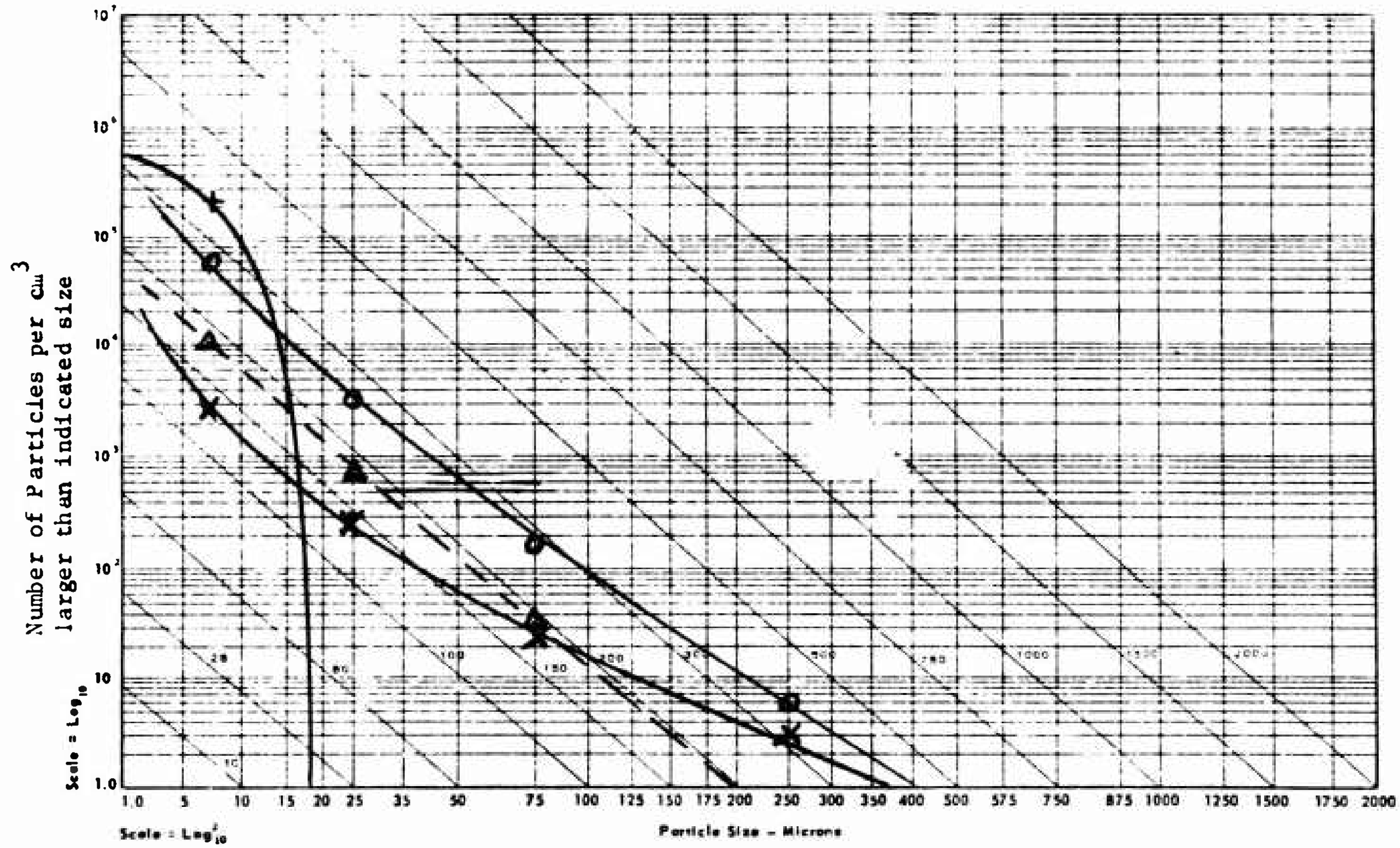
$$\log \ln (1/N) = m \log X + \log B$$

Orr states that "B tends to be characteristic of the solid material while the value of m shifts according to the spread of the distribution."

3.9 Particle Size Distributions

Those engaged in the analysis of data on the number of particles (n) took up a more sophisticated theoretical equation, known as the "log-normal distribution." This is based on the primary concept that many phenomena involving a large number of similar events result in a "normal" distribution of frequencies of sizes, with 50% clustered near the mean and the rest stretching out to extremely large and small. This model is often called "Gaussian" after the mathematician who developed the equations from basic principles of probability. Other phenomena require only half of the bell-shaped curve, the mean being zero and the other half giving negative or imaginary diameters. Still other phenomena fall off in frequency so rapidly as size departs from the mean that they are best described by using the logarithm of the frequency in the Gaussian equation. This is the "log-normal."

The aerospace industry found the log-normal mathematics overly complicated, and introduced the equation shown in the legend of Figure 14. While this is often referred to as "log-normal," it is not, and must be



Research shows that naturally occurring particulate contamination follows a log-normal distribution with a geometric mean of near one (1) micron particle. This distribution follows a straight line when plotted on a log x log^2 scale graph. The grid is derived from the log-normal or Gaussian distribution function which provides a close fit to real contamination data. The lines on the chart represent the maximum contamination permitted for each level and the plot point is the number of particles above given size versus particle size. The curves can be expressed as $\log n = 0.9260 (\mathrm{Log}^2 X_1 - \mathrm{Log}^2 X)$, where n is the number of particles, 0.9260 is the tangent of the angle, X is the particle size, and X_1 is the cleanliness level.

O CHIPPING FRACTURE
+ ABRASIVE MODE
× IMPACT FRACTURE

△ COMPOSITE MODE = 89% IMPACT
10% CHIPPING
1% ABRASION

ALL DATA CONVERTED FROM WEIGHT FRACTIONS QUOTED BY ORR (38).

Figure 14. Characteristic Curves for Modes of Partic .e Fracture.

regarded as a purely empirical "log-square" model. However, it is extremely useful.

Both the log-normal and log-square have the same logical defect in that they predict that N will grow without limit as X decreases. This prediction of a vast population of particles between 1 μm and molecular diameter is simply not true. Any size reduction process ceases to be effective when the particles reach a critical diameter below which fracturing forces cannot be brought to bear. Steiger (39) recently proposed using the Weibull distribution, which can include a correction for this fact:

$$\log \ln (1/n) = \ln \alpha + \beta \ln (X - \gamma)$$

where n is the number of particles larger than diameter X, α corresponds to B and β to m in Section 3.8.4, and γ is the minimum diameter (usually about 0.1 μm).

3.9.1 Irregular Distributions are those in which n and X do not produce a straight line when plotted on any of the above distributions. This is true of all three fracture processes in Figure 14, though the summation line does plot well on the log-square paper. It would not be very surprising if it also plotted well on one or more other distributions, since sometimes the differences are within experimental error.

The abrasion curve can be described as "truncated," meaning that the larger particles are missing. Another form of irregularity is "bimodal," such as a mixture of dust and gravel with no sand.

3.9.2 The Spread of a Distribution is an experimentally determined value, not inherently provided by the fact of normality. The spread of a normal distribution is defined by its standard deviation, while that of a log-square is defined by its slope "m." Fitch (40) and others have shown that a slope m = 0.9260 fits stream bed debris, hydraulic oil contamination and a variety of other materials. Another style of paper devised by Fitch is shown in Figure 15. This slope is not always found. In Figure 7, fatigue wear produced a distribution of m = 1.115, while scuffing gave m = 1.600. In this report, m = 1.00 ± 0.15 will be called "standard log-square" while m > 1.15 will be called "steep log-square."

3.9.3 Effects of Filtration and other particle removal processes can take various forms. Screens tend to produce truncated distributions. However, depth filters (which include the popular Millipore membranes despite some fanciful sketches in the past) tend to produce a log-square distribution of the original slope, moved downward on Figure 14. There is no completely logical explanation for this experimental fact, though there are some plausible ones. A very interesting point is that screens which have

39 Steiger, F. H., "Practical Applications of the Weibull Distribution Function," CHEM TECH, April 225-231 (1971).

40 Fitch, E. C., "Requirements for an Effective Program in Fluid Contamination Control," ASTM STP 491, pp. 39-49 (1971).

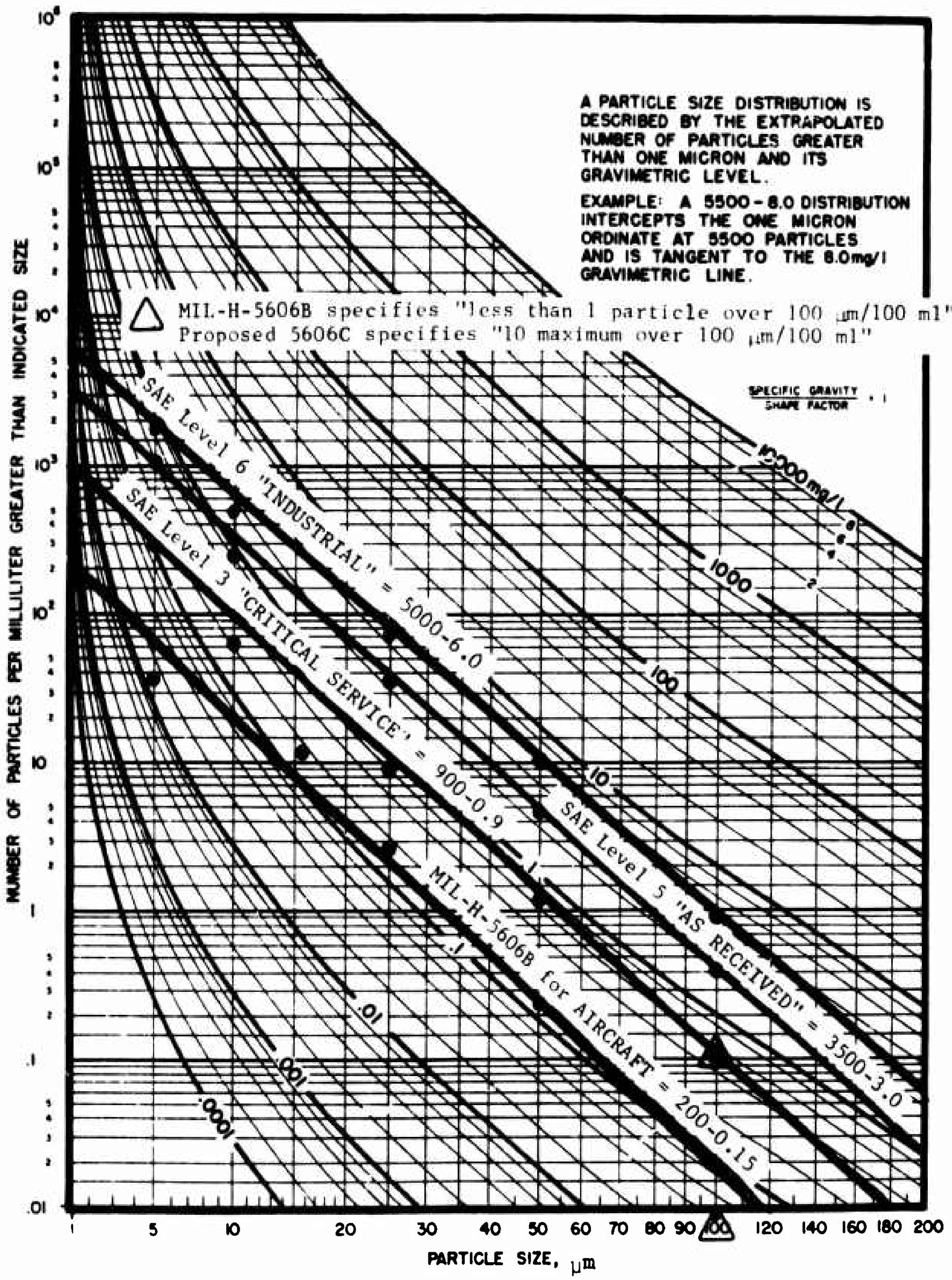


Figure 15. OSU Particulate Contamination Chart (typical SAE and MIL levels added).

accumulated a layer of particles become depth filters and hence the effluent changes from truncated to log-square.

Sedimentation tends to increase the slope in the upper layer, while the bottom layer will tend to $m < 1.00$. The controlling settling times are shown in Figure 16. Centrifuging and magnetic separation have similar effects, less easily predicted.

3.9.4 <u>The Predictive Power</u> of the standard log-square distribution is tremendous. In plots like Figure 14, determining the size of the largest particle present at one per cm^3 is sufficient to define the whole population, since this is the intercept B in 3.8.4. Even nonstandard slope distributions may be defined by two measurements.

3.9.5 <u>Various Particle Populations</u> anticipated from different wear modes are shown in Table 5. This is modified slightly from the version presented in 1971 (1). There is room for further experimental investigation on many details. However, enough is known to establish quite definitely that any complex wear process will produce a wide spectrum of sizes. Since no known detection method covers this entire spectrum, as shown in Section 5, the inevitable conclusion is that at least two methods are required for reliable prognosis.

3.10 Recirculation of Particles

As mentioned above, the primary particles from a wear process may not be evident in the system. A good many may be trapped by filtration and/or magnetic plug attraction. Another mode of loss is by settling, as shown in Figure 16, from Reference (1). All three modes tend to be quite selective towards removal of the coarser particles. However, as discussed in Section 5, the filter or magnetic plug can serve as a tool for prognosis.

Particles which are missed by these processes continue to circulate, and tend to be caught in bearings or gears. This is a statistical process, in that it would take a bearing about 0.5 year to catch any specific particle in the SKF type R-2 test machine (19). The basis for this is the volume under the six loaded balls. Each of these spots in a 6039 bearing is estimated to be 8 mm wide, 0.8 mm long, and 0.25 μm thick. Hence, the total active volume is 9.6×10^{-6} cm. At 3000 rpm, the oil in this gap is renewed at $5 \times 10^{-4} cm^3$ per second. Assuming that the 7500 cm^3 (2 gal.) of oil in the system passes through the gap in orderly fashion without backmixing, one complete pass requires 1.5×10^7 seconds, or 174 days.

Catching one of the largest particles detectable in a 1-cm^3 sample, which is the size implied by the "SAE level" lines on Figure 15, requires only 33 minutes. If this is 60 μm in diameter, which would be cleaner than the average helicopter system, the log-square model shows that it will be accompanied by about 100 particles of 10 μm or greater diameter. One of these would be caught, on the average, every 20 seconds. It is not generally appreciated what it means to pass a 10 μm particle through a typical bearing gap of 10 μ-in., since most engineers are unfamiliar with the μm

Table 5. Contamination Processes and Products

Process	Particle Diameter (μm)	Expectancy in Aircraft Engines, Transmissions and Gearboxes
Corrosion	Gross sheets, grinds to fine dust	Probable in gearboxes
Fretting	0.10 to 5	Only in some designs
Fretting Corrosion	0.10 to 5	Only in some designs
Sliding Fatigue	Standard Log-Square (Figure 7)	Only after zero-wear period (Figures 4 and 5)
Scuffing (Smearing)	Steep Log-Square (Figure 7)	Only during failure of gears, etc. (Figure 5)
Corrosive Wear	3 to 5 (oxide)	Probable
Normal* Wear (Surface Distress)	3 to 5 (metal)	Probable
Rolling Fatigue	Not certain	Probable, after a high cycle zero-wear period
Abrasion	1 to 15 (Figure 14)	Certain, after critical concentration of particles due to other processes is reached
Ingested Dirt	Standard Log-Square	Certain, on intermittent basis
Beilby Layer Extrusion	Slivers	Gears only, late in operation. See Table 3.
Spalling of Case	50 to 500+	Gears and roller bearings, after induction period. See Appendix A - 1.2.2 and 2.1.
Quench Cracking	500+	Gears only, early in operation. See Appendix A - 1.3.5

* Combined modes, found in machines operated on Stop/Start basis.

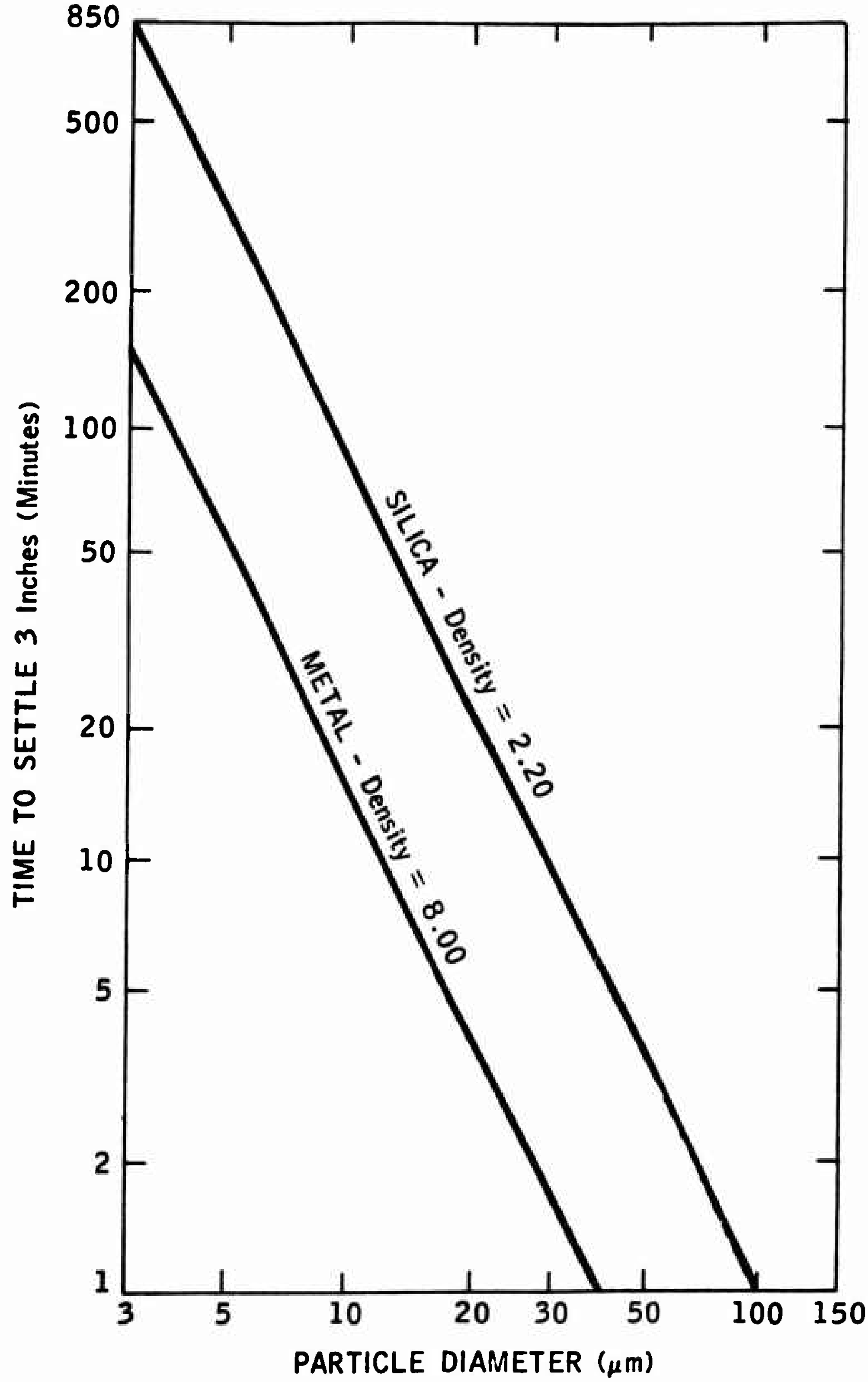


Figure 16. Settling Rate of Spherical Particles in Oil of 5 centistoke Viscosity at Sampling Temperature (210°F)(Oil density = 0.90).

and most scientists with the μ-in. Actually, these units are in a 40/1 ratio, so the passage is roughly comparable to pushing a football into your ear. The result must be quite like a cold-rolling steel mill. While the bearing has a diametric clearance of 5 to 20 μm, this impact is so sudden (about 1μ sec for a point on the ball to travel 10 μm) that inertia essentially rules out vertical deflection and the accommodation must be by deformation or fracture. This causes the dents discussed in Section 2.3.3, and at least part of the flaky particles found by Westcott (13). Of course, gears are more capable of flexing than bearings and so may not flatten particles so severely, but their longer gap means more rapid access to all particles in the system.

Ingested dirt reacts quite differently, and fractures as described in Section 3.8.1 by impact. Samples from Delta Air Lines were examined in great detail. As mentioned in Section 2.5, the dirt had been ground to such a fine powder that it presented no hazard.

3.11 Large Particles, or chips, are a special category. They tend to arise at several stages in the history of an item. Despite the rigorous precautions taken, sometimes there are chips left in during assembly, and further chips may be generated during the "green run" at the factory. None of these chips should reach the field, but there have been slips. These, combined with some other manufacturing defects and occasional rough usage before run-in is complete, lead to the well-known high initial failure period of the "bathtub curve" cited by Dougherty (29). The chips found during this period may include assorted "junk" (lock nuts, washers, retainers, etc.), along with tooth corners and other points vulnerable to quenchcracking during heat treatment.

Following this, there is a long period of essentially chip-free operation, corresponding quite closely to Bayer's "Zero-Wear" period (6) and the minimum assured life found in fatigue tests (41) showing deviations from the Lundberg-Palmgren L_{10} concept (14,15). The coarse particles which next appear are typical of fatigue spalling, being flaky whether from bearings or gears. This is the beginning of the upswing on the bathtub curve, and is the precursor of an accelerating crop of chips (sometimes without ASOAP warnings). If proper chip detection devices are in service, this warning comes while the aircraft has a good many hours of safe flying left.

The prognosis of "how many hours" is difficult to answer. The discussion proper is in Section 6, but the point can be made here that this prognosis can depend on diagnosis. If the chips can be clearly identified as gear material, the curve in Figure 5 indicates that sliding fatigue tends to decelerate after the first shower of chips. Whether this is exactly true or not, gears are well-known to be more tolerant than bearings, and many automobiles are operating quite safely on gears that ASOAP would have called in long ago.

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41 Tallian, T., "Weibull Distribution of Rolling Contact Fatigue Life and Deviations Therefrom," ASLE Trans., 5, 183-96 (1962).

Diagnosis of the chips as bearing metal is less reassuring, though some bearings fail in sliding fatigue. However, on the logical basis of "worst assumption," this diagnosis would predict a constant wear rate. The various transmission engineers tend to agree that bearings have less "forgiveness" than gears, but have experienced 50 hours or more from first detection to loss of function. They also agree that taking undue advantage of this extra time can lead to a great deal of secondary damage, so the cost-effectiveness is soon wiped out.

A study by Spano* at Fort Rucker on CH-47 failures showed the presence of "slivers" (Appendix Table B-5). These have long been known in automotive hypoid gearboxes, and result from plastic flow of metal along the tooth surface from the dedendum to the addendum. This Beilby layer eventually protrudes as a wire edge, and breaks off to form the chip. Along with this flow, ripple marks develop as mentioned in Table 3. This is one mechanism which generates chips without giving an ASOAP signal. Two others are quench cracking and case spallation (Table 5).

3.12 Organic Particles

Unlike the automobile, turbine aircraft do not develop much particulate matter from the oil. The specifications require such thermal and oxidative stability that lacquering, etc., are rare. However, the Trans-Sonics studies (13) have shown that the wear particles can react with the oil. This would be expected from the known increase in reaction rate of freshly sheared metals, called "mechanical activation" (5). This can lead to some of the metal going to a metallo-organic form, and the particle growing a "plastic coating." Such composite particles tend to evade the ASOAP method, since they have grown to a size likely to be lost.

The other, and main, source of organic particles is the seals. There has been so much trouble with silicone rubber in particular that the presence of red rubbery bits, with high silicon readings on ASOAP, has become a routine problem. Some of this silicon is actually in solution but much of it is visible under the microscope. It does not seem to have any value for prognosis.

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* Spano, E. F., personal interviews on January 15 and April 2, 1974.

4. Surface Defects Caused by Bearing Wear

The examination of worn bearing surfaces is mainly of diagnostic value and bears only indirectly on prognosis. However, no prognosis system can be expected to function without constant feedback from the diagnostic facility, in language clearly understood by both groups. This section is designed to illustrate the wear modes, tying them in to the particle sizes and shapes noted in Section 3 as much as possible. To draw on the SKF library of illustrations (42) it was necessary to reconcile current bearing damage terminology for wear modes with that used in Section 2.

For comparable illustrations of damaged gear surfaces, the reader is referred to Bowen's report (26).

4.1 Abrasive Wear

Abrasive wear in a cylindrical roller bearing is shown in Figure 17. The wear caused by abrasive contaminants is evident at the roller end (A), against which the flanges have rubbed and removed a macroscopic layer of material. The worn surface is smooth, not pitted. Hard, apparently brittle particles (abrasive grit, sand) caused dents with sharp edges on the bearing rolling surface shown in Figure 18. Dent bottoms are smooth and shiny.

A 30X optical micrograph of the abrasively worn rolling surface of a bearing ring operated in the presence of hard contaminants is shown in Figure 19. Little directionality, a number of depressions, and a generally matted or "sanded" appearance resulted.

An abrasively worn surface of a bearing operated in the presence of hard contaminants is shown in Figure 20. A long sharp-edged cut indicates an individual wear occurrence in the presence of some sliding. A sharp object (asperity or hard particle) was pulled across the surface and cut a gouge. The remainder of the pitted surface is without specific indications of individual mechanical wear events. This is common in predominantly rolling contact, probably because wear gouges are subsequently obliterated by rollovers. A general ablation of surface material is evident from the absence of all finishing marks.

A higher magnification of the same surface, Figure 21, shows the irregularly deformed, generally pitted condition present after abrasive wear under predominantly rolling contact. In the absence of identifiable wear marks, diagnosis of a specific wear phenomenon is uncertain.

Figure 22 is a low magnification photograph of a worn surface on the center flange of the spherical roller bearing over which the cage moves in simple sliding. The wear band extends from line A-A to line B-B. An appreciable layer of material has been removed. The longitudinal scratches

42 Tallian, T., et al, Rolling Bearing Damage, a Morphological Atlas, Library of Congress Card No.74-81983, SKF Industries, Inc., Philadelphia (1974).

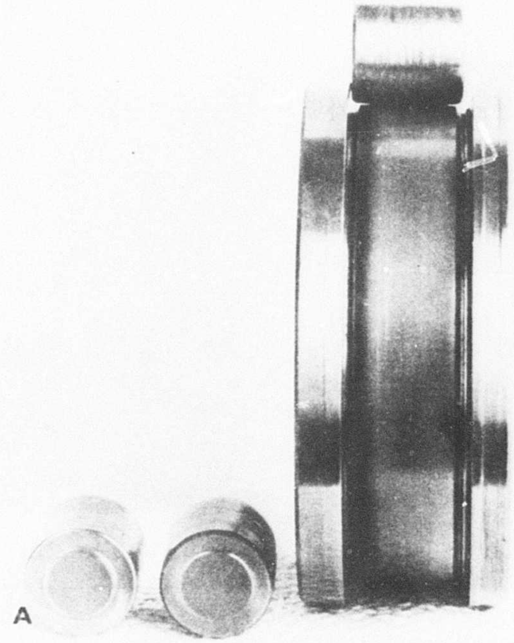

Figure 17. Abrasive Wear in a Cylindrical Bearing. (1X)

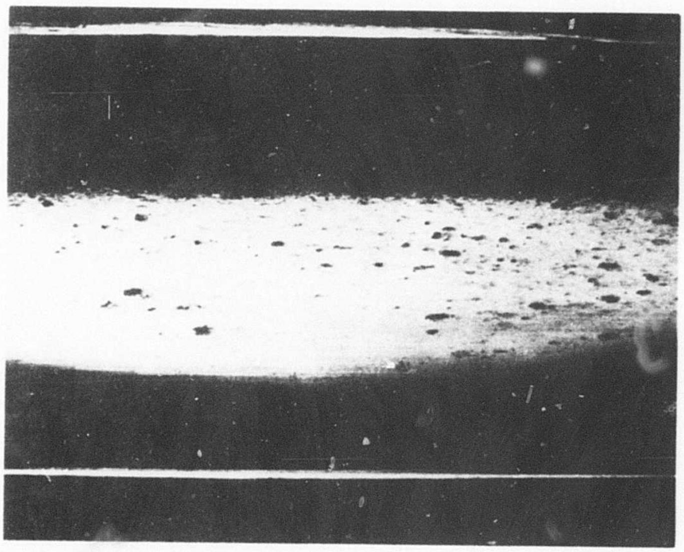

Figure 18. Debris Dents Caused by Hard Particles. (10X)

Figure 19. Optical Microgram (30X) of Abraded Surface on Bearing Ring.

Figure 20. SEM Microgram (300X) of Abraded Surface.

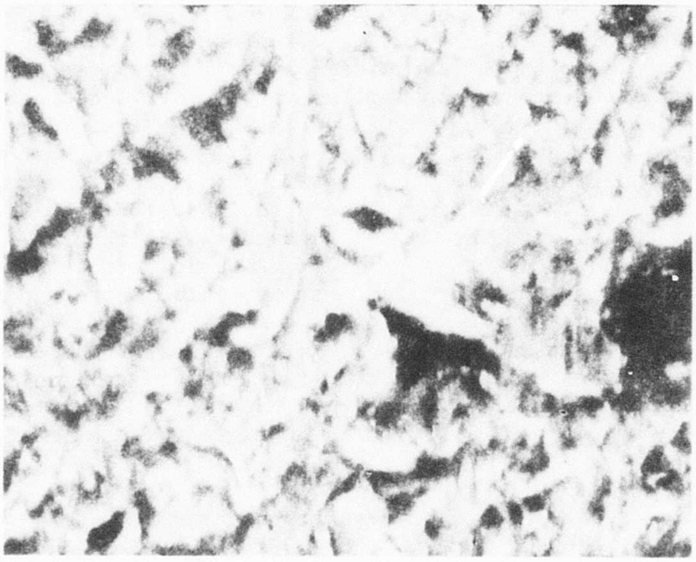

Figure 21. SEM Micrograph (3000X) Showing General Background Produced by Abrasive Wear.

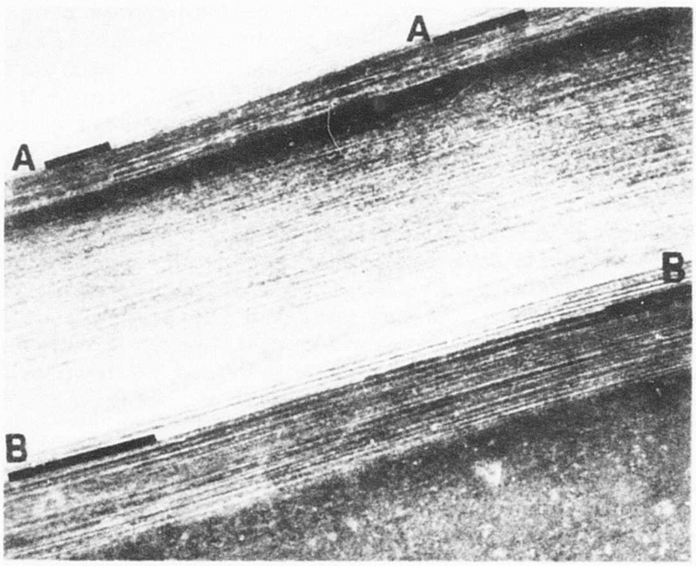

Figure 22. Abrasive Wear Produced by Simple Sliding Contact. (25X)

indicate the direction of sliding during wear. Since there is no lift-off in simple sliding surfaces, the scratches are very long and directional.

Wear marks of definite geometry often occur on surfaces rolling with some sliding. These are called kinematic wear marks as they are caused by the impression of an opposing asperity (or imbedded particle) and motion over the surface according to kinematic laws determined by the rolling and sliding configuration of the contact. They are most easily recognized in ball bearings where they are fingernail or horseshoe shaped due to the spin component of sliding. The duration of contact is precisely set by kinematics for an asperity moving through the Hertz area, causing the sharp beginning and endpoint of the mark. A multitude of kinematic wear marks are shown in Figure 23. The marks vary in length and curvature depending on location in the track. Note old marks partially obliterated at (A), new sharp-edged marks at (B). The micropits at (C) are not typical of this condition, but often appear secondarily on worn rolling surfaces, due to microspalling of plastically deformed material. Bearing surfaces having a multitude of kinematic wear marks or micropits are sometimes called "frosted."

The particles from this process are usually too small to have any value in prognosis by shape.

4.2 Rolling Fatigue

4.2.1 The classical failure mode of a rolling contact between hard steel surfaces is high-cycle rolling fatigue. All life data given in rolling-bearing catalogs predict the useful life to termination by a spalling failure on one of the parts. Gear-rating formulas also take account of spalling (pitting) failure. A spall is the void remaining in a contact surface after a flake of metal has been removed by a complex process which is not yet fully understood. Figure 24 shows a spall in a hardened steel raceway of a bearing. The walls and bottom of the crater are formed of fracture surfaces. The crater is sharp-edged, steep-walled and flat-bottomed. Figures 25 and 26 show two steps in the progression of spalling in a ball bearing race.

4.2.2 Another form of rolling fatigue is surface distress, which is a precursor of surface initiated spalling. The designation "surface distress" signifies a peculiar sequence of damage to rolling surfaces, characterized by the initial absence of mechanical wear and the presence of plastic deformation on the asperity scale. Surface distress progresses to cracking and microspall formation. These may be attributed to low-cycle fatigue, comparable to that found in sliding (see 3.4.2 for the question of particle shape).

Figure 27 shows at (A) the highly burnished "glazed" area indicative of early stages of surface distress, and at (B) the surface distress has proceeded to microspalling and yields a frosted appearance.

Figure 28 is a higher magnification photograph of a heavily glazed surface with bands of surface microspalls, and Figure 29 is an SEM microgram

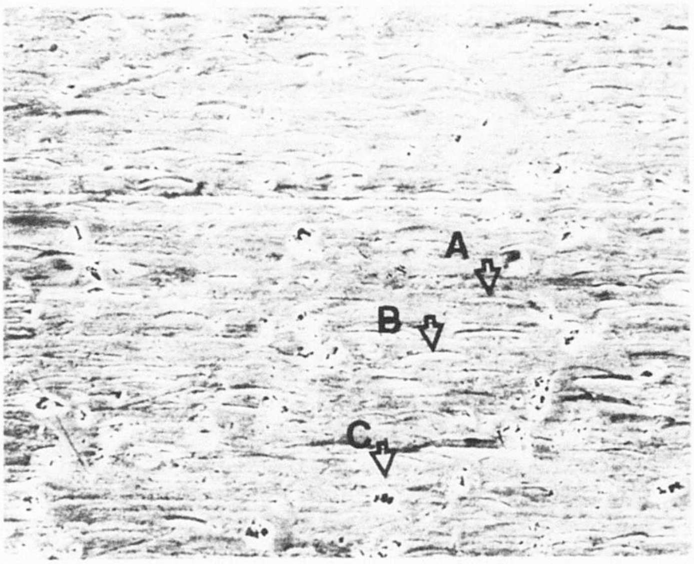

Figure 23. SEM Microgram (1000X) Showing Kinematic Wear Marks.

Figure 24. Optical Microgram (25X) of Spall.

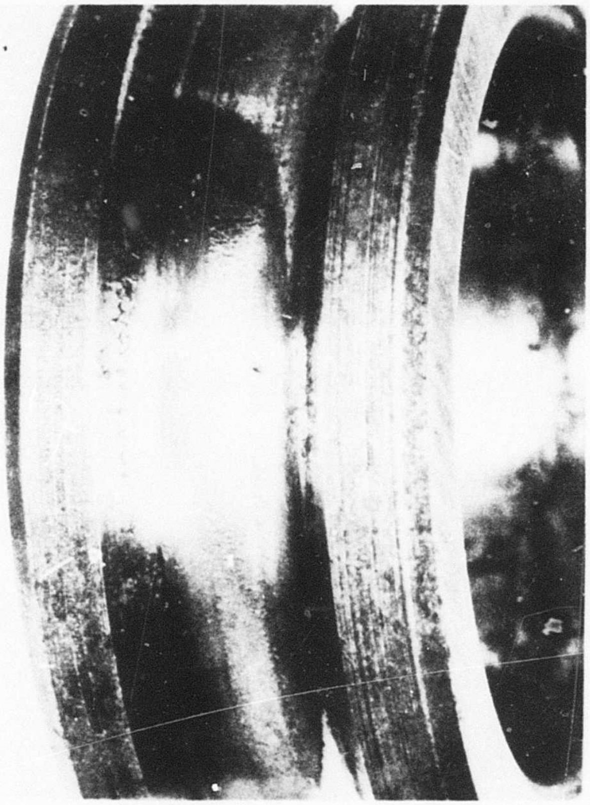

Figure 25. Two Small Spalls in Bearing Race. (2X)

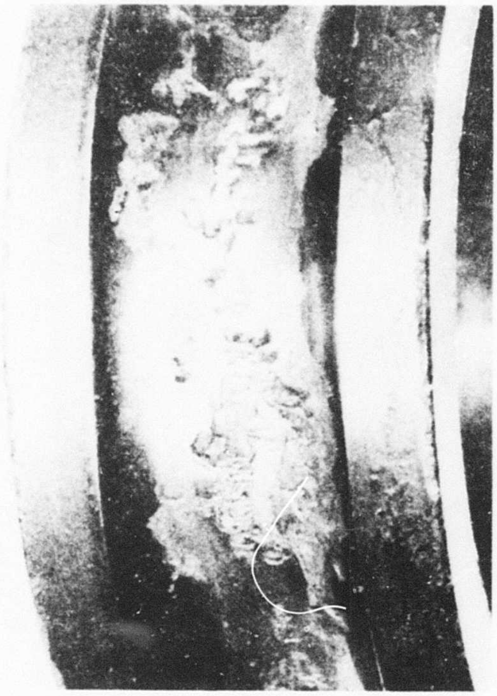

Figure 26. Extensive Spalling of Race. (2X)

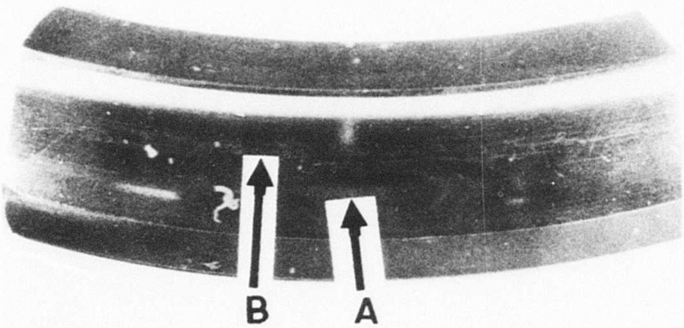

Figure 27. Macro Photograph of Surface Distress in Bearing Ring. (2X)

Figure 28. Optical Microgram (50X) of Advanced Surface Distress.

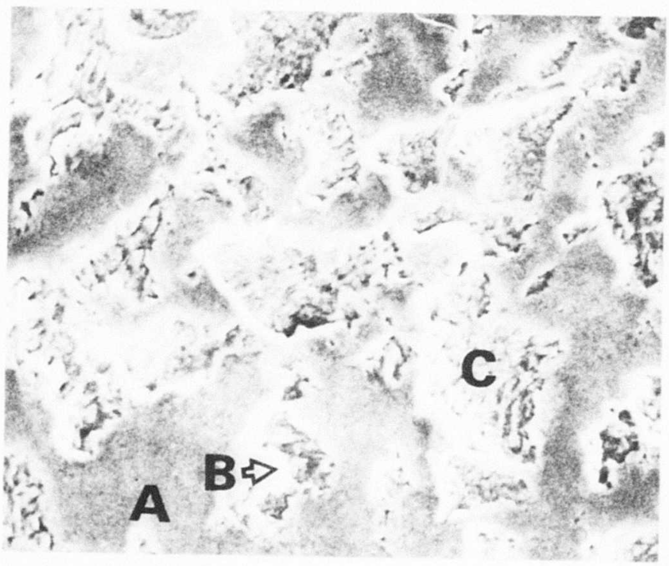

Figure 29. SEM Microgram (1000X) of Surface Distress.

of a distressed surface. Note the smooth "burnished" surface (A) "feathered edges" of plastically flowed material (B), and fracture surface in the microspall bottom (C).

Surface distress sometimes occurs locally as a "halo" of glazed surface surrounding a surface defect such as a debris dent or a deep scratch or furrow, like the one shown in Figure 30. The elliptic outline is the plastically deformed glazed area within which the black irregular shapes are microspalls.

4.3 Severe (Adhesive) Wear

In contacts undergoing appreciable sliding (possibly in addition to rolling), a severe type of wear can occur, which is referred to as "smearing" or "galling." Smearing is diagnosed when the following conditions are met:

4.3.1 Metal, tightly bonded to the surface, is present in locations into which it has been transferred from remote locations of the same or opposing surfaces.

4.3.2 The transferred metal is present in sufficient volume to connect more than one distinct asperity contact. When the number of asperity contacts connected is small, it is referred to as microsmearing; when it is large enough to be visible with the unaided eye, it is called macroscopic or gross smearing.

Skid-marking is a form of microsmearing followed by microcracking and peeling of the thin smeared surface layer, sometimes encountered in high-speed engine bearings. Figure 31 is a photograph of a skid-marked ball surface. The marks are the light-colored frosted areas (A). At (B), a scratch separates the skid marks from unmarked areas. This preexisting discontinuity has prevented spreading of the material transfer.

Smearing is often progressive from micro to macro. Gross smearing is often the cause of catastrophic failure in a bearing, leading to heat imbalance, high vibration levels, loss of accuracy, and occasionally seizure and fracture. However, even gross smearing can spontaneously be arrested, e.g., if the operating conditions improve. The surface may polish over in further running without leading to catastrophic failure.

4.3.3 Due to the mechanism involving the transfer of material from one contacting surface point to another, smearing requires the presence of sliding motion between the surfaces. For that reason smearing often occurs on cage contact surfaces, as shown in Figure 32. In rolling, smearing has not been shown to occur. Figure 33 is an SEM microgram showing smeared material crossing preexisting finishing marks.

Smearing in the race of a ball thrust bearing in which sliding as well as rolling occurs from the ball spinning motion is shown in Figure 34. The dark appearing diagonal hatchmarks or streaks in the groove (A)

Figure 30. Optical Microgram (85X) of Local Surface Distress.

Figure 31. Optical Microgram (25X) of Skid Marks on a Ball.

Figure 32. Cage Smearing.

Figure 33. SEM Microgram (500X) Showing Smeared Surface.

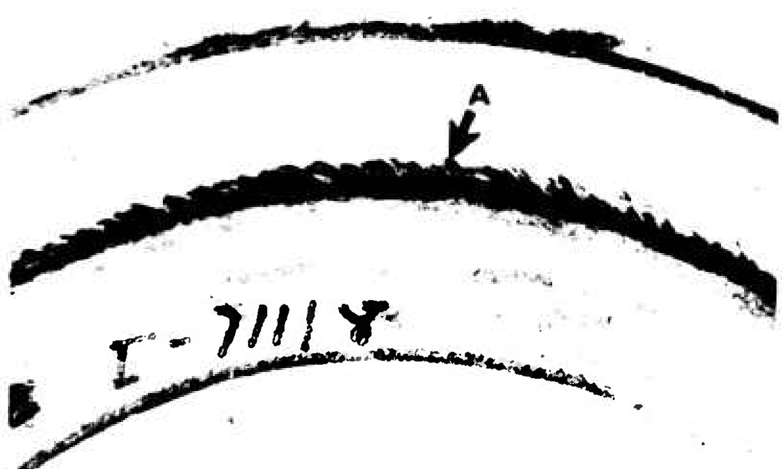

Figure 34. Smearing in Ball Thrust Bearing. (4X)

consist of transferred metal. Smeared metal can appear either dark or light against the unsmeared background, depending on illumination.

In a roller bearing the roller ends contact a ring flange and move in combined rolling and sliding over the flange. Figure 35 shows smearing which occurred on a roller end.

When smeared metal detaches from the surface, the resulting particles are sure to be flaky.

4.4 Corrosion

The finely finished surfaces of ball and roller bearings and gears, excluding those made of stainless steel and special materials, are readily subject to corrosion by water, acid and other agents. Figure 36 shows rust spots on the end of a roller, caused by water mixed with the grease. The corroded roller shown in Figure 37 resulted from acids in the lubricant. This type of corrosion leaves a multitude of dark-bottomed pits, the surroundings of which are polished by running. This condition subsequently creates extensive surface-originated spalling, from a multitude of initiation points. Corrosion spots and streaks shown in Figure 38 were created on the raceway of a bearing, by moisture in the lubricant. A small amount of circumferential motion in the bearing, subsequent to the introduction of the wet lubricant, led to the streaky corrosion. The sort of particle generated is shown in Figure 11.

4.5 Fretting and Fretting Corrosion

Fretting corrosion and false brinelling, though resulting from the same phenomenon and considered to be the same, are differentiated in bearings according to location.

Fretting, as distinct from false brinelling, is mild (adhesive) wear of surfaces other than rolling contacts when subjected to oscillating motion of very small amplitude. Fretting damage is most common at the fit surfaces of rolling bearings (inner ring bore to shaft, outer ring O.D. to housing). Fretting is characterized by the removal of extremely small wear particles, often followed by immediate local oxidation. This local oxidation creates corrosion products similar to rust. The distinction between fretting corrosion and conventional corrosion can be made by considering its location and distribution. When an otherwise uncorroded bearing part shows brown corrosion stains often surrounded by burnished areas, only at the contact surfaces, fretting corrosion is likely (see Figure 39).

False brinelling is defined as localized fretting, arising when rolling elements of a bearing oscillate with small amplitude while pressed against a race surface, as in a stationary bearing subjected to vibrations. The material removal proceeds in stages: (a) asperities adhere, are torn apart and form wear debris; (b) due to the smallness of the motion, the wear debris does not escape readily and acts as an abrasive for further wear. The wear pattern is a depression similar to the brinell mark obtained

Figure 35. Smeared Roller End. (2X)

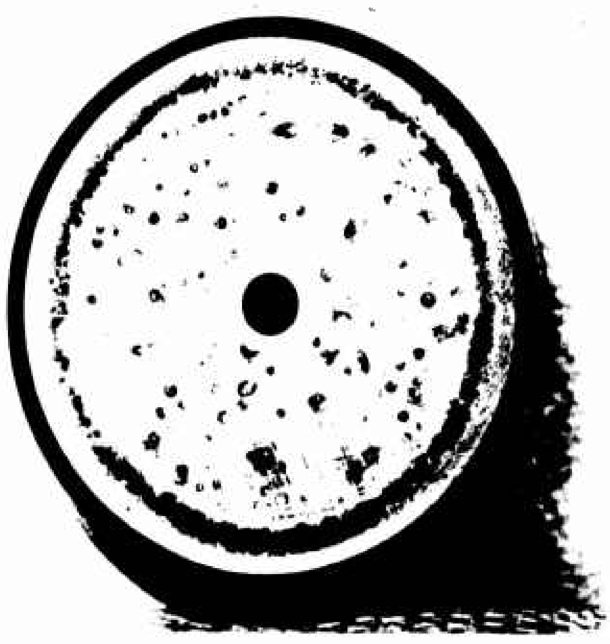

Figure 36. Corrosion on End of Roller. (2X)

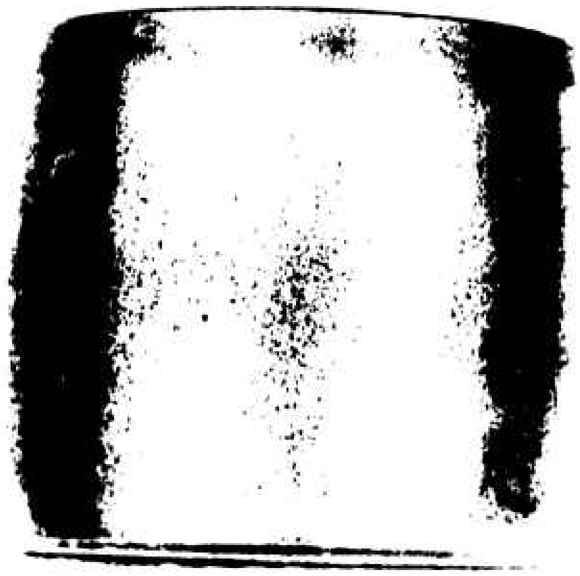

Figure 37. Corroded Roller. (2X)

Figure 38. Corrosion Streaks in Bearing Race. (10X)

Figure 39. Wear Due to Fretting Corrosion.(.75X)

Figure 40. False Brinelling Caused by Vibration with Bearing Stationary.(.5)

by static overloading, see Figure 40. Hence, the designation "false brinelling." The distinguishing feature of false brinelling over true brinelling is the absence of finishing marks at the bottom of the false brinell depression. A matted wear surface appears instead.

5. Detection Methods

There are many methods for detecting wear debris in used oil that have been used or suggested for prognosis. This section takes up those which are either in or ready for production, and touches lightly on a few of those still under development. The primary aim is to establish the virtues and limitations of each method in order to explore the possibility of using more than one channel of information.

It is evident from Section 3 that information with potential for prognosis is accessible at many points in the size "spectrum" shown in Figure 41, from 1 μm to 1000 μm. It may be less evident, but undue concentration on one size range to the exclusion of all others can blind the user to much valuable information. A third point is that the user should select very carefully the type of data to be collected, to avoid losing cost-effectiveness through redundancy.

The following sections discuss the principles of detection without much linkage to specific hardware. Appendix D provides some information on the availability of detectors to implement these principles

5.1 Spectrographic Analysis

There is no need to discuss the principles and virtues of the present ASOAP procedure, as these are well-known. What is not so well recognized is that there are inherent blind spots in this method. The best known of these is the size limitation. This was shown by Bond (34) in a series of experiments conducted for the Navy. Large samples were drained from each of two failed reciprocating and jet engines. Each sample was then subdivided into subsamples which were processed in four ways: (1) unfiltered, (2) filtered through an 8 μm GE Nuclepore membrane, (3) filtered through a 5 μm Millipore SMWP membrane, and (4) filtered through an 0.65 μm Millipore DAWP membrane. Only the jet engine samples are discussed below, though the others gave quite similar results. Each subsample was analyzed in quadruplicate (or more) on an A/E 35 U-3 emission spectrometer and a Model 303 AA spectrometer.

The results indicate that no substantial reductions in the amounts of the 12 metals reported by either of the spectrometers resulted from 8 μm filtration. This could conceivably happen because both spectrometers happened to be blind to 8+ μm particles. However, this is a most unlikely coincidence. Furthermore, if such particles reached the spectrometers, at least some would burn and the critical diameter would vary from metal to metal. On the other hand, Figure 16 predicts that all such particles would be lost by settling, so it may be concluded that they were lost in the sampling process, and that ASOAP is blind to them for that reason.

The 0.65 μm filtration removed essentially all of the metals, with a few exceptions as discussed in Section 3.4.2. This is quite consistent with the size reduction models in Section 3.9.4, which predict that particles below a critical diameter will not be formed. This is not, of course, a handicap to ASOAP.

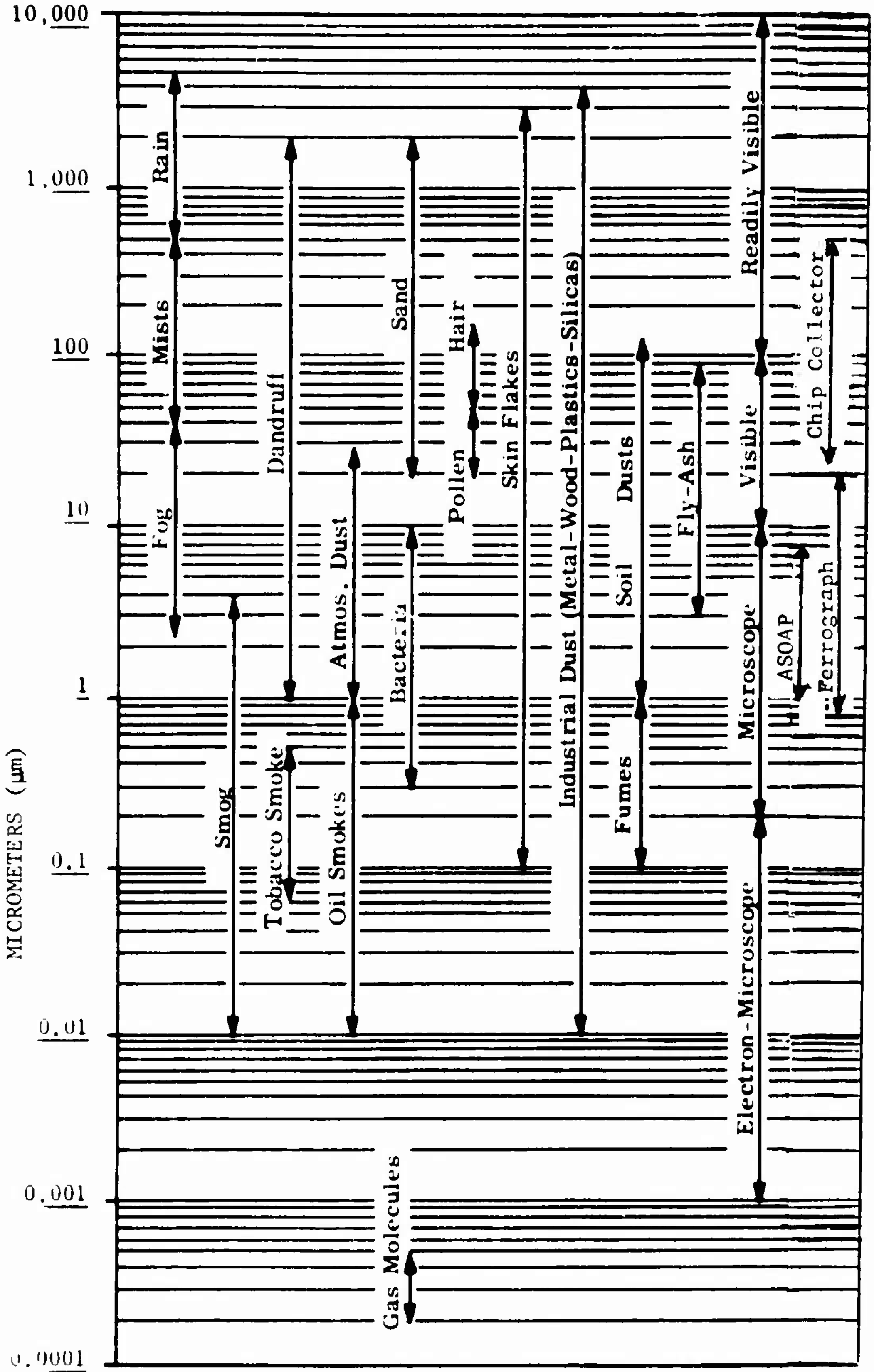

Figure 41. Spectrum of Particle Sizes.

Another limitation that is also well-known is that the spectrometer reports only the elemental analysis and is blind to chemical form. To differentiate between a metal wear particle and that metal's corrosion product, the ASOAP laboratory must go through these steps:

- Instruct the maintenance shop to drain and refill the lube oil, run for 10 minutes, and sample.
- Wait for 5 flying hours (about a week).
- Obtain another sample from the shop.
- Run ASOAP and compare results.

If the laboratory chief was right in suspecting corrosion, both the 10-minute and 5-hour samples will show much less metal than the one causing concern. However, if wear is really going on, there will be a substantial increase during the 5 flying hours. This procedure works quite well, except when the shop crew fails to drain all the oil or another crop of corrosion develops.

Blindness to particle shape may not be a very serious handicap, since the role of shape in prognosis is limited as discussed in Section 6.

The success of the ASOAP program has been the subject of a great deal of debate, and it was hoped that this study would provide definitive answers. However, due to scheduling problems at AAVSCOM it was not possible to correlate the ASOAP data with teardowns, except for a few cases on CH-47s and TH-55s, so it was necessary to draw on data from the U.S. Navy and U.S. Air Force. Unfortunately, both services use mostly fixed-wing aircraft. Before discussing them further, it is essential to state the definitions of certain terms:

- Removal - taking a component to the depot overhaul shops for any reason. However, in this paper it covers only the cases where the cause was a SOAP prediction, or should have been.
- HIT - a removal for which the SOAP prediction was found to be justified.
- MISS - a SOAP-based removal not found to be justified.
- Success - the percentage of SOAP-based removals which are HITs.
- FAIL - a removal caused by field evidence (noise, vibration, chips etc.) which should have been predicted by SOAP, but was not.

The data available from the three services may be summarized as follows:

5.1.1 The transmissions on the CH-47s at Fort Rucker showed 32/34 (94%) success.* Transmissions on the TH-55s at Fort Wolters (43) showed 62/75 (83%) success before improvements discussed below (see 5.9) were made. The entire ASOAP program showed 273/322 (82.5%) success in 1971.**

5.1.2 The Navy program was discussed by Ward (44) in 1968. Their success rates were 80% on reciprocating engines, 90% on jet engines and 92% on transmissions plus gearboxes. The number of removals on these were not given. Meserole (1) reported 39/40 (97.5%) success in 1971, on engines at the North Island Naval Air Station. Short (45) reported on the 1973 removals from a portion of the Navy aircraft selected for a special computer run. Fixed-wing aircraft engines (largely jets) showed 94/123 (76.5%) success. Helicopter engines showed 20/29 (69%), the transmissions 4/9 (56%) and the gearboxes 2/9 (22%). For details, see Appendix B.

5.1.3 The Air Force reported in 1971 that their success was over 95%, with no details given (1). In 1973, their fixed-wing aircraft engine success was 1241/1293 (96%). No helicopter engines were removed that year. Transmissions showed 17/18 (94%). Gearboxes were taken off SOAP several years ago because it was not considered to be effective.

5.1.4 The Army and Navy were not able to provide any estimate on FAILs and the Air Force had none on helicopters. On the C-130 (T-56 engine) the first six months of 1973 gave

HITs	=	76
MISSs	=	9
FAILs	=	10

This was considered fairly typical, with the FAIL and MISS rates about equal. This FAIL rate can be accepted, especially on multi-engine aircraft.

5.1.5 The wide discrepancies among services can be attributed to several causes. Probably the largest factor is that the Air Force depends mainly on trend analysis, though their manual (46) still shows guidelines

* Dougherty, J. J., personal interview at The Boeing Co., Vertol Div. (May 16, 1974).

** Hoffman, R., personal interview at AAVSCOM, October 31, 1974.

43 Newlin, K. D., "A Statistical Analysis of Spectrometric Oil Data from the Transmission of the TH-55A Helicopter and Recommended Improvements for the ASOAP Program," Texas A&M University, for USAMC Intern Training Center, Red River Army Depot, May, 1970, AD 739 152.

44 Ward, J. J., "Navy Spectrometric Oil Analysis Program," SAE Preprint 680213, April 3-5, 1968.

45 Short, R., and Watson, J. O., "Feedback Status," Naval Weapons Systems Analysis Office, 1974

46 Air Force Technical Manuals T.O. 42B2-1-9 (1 July 1972) and T.O. 42B2-1-10 (1 August 1970) and revisions.

for both ES and AA spectrometers, along with many footnotes for special cases, they do not remove a module until a definitely increasing trend has been observed.

The Navy is in the process of changing over from condemnation limits to trend analysis (47), and their lower success in 1973 may reflect this fact. They also tend to be more conservative since FAILs over water are especially serious.

The Army has few enough laboratories that they can keep in close touch and so have not required as formal a policy on evaluation. However, they do use trend analysis as the basic tool.

5.1.6 The overall picture is that DoD is achieving 80% or better success on engines. The Army evaluators feel this level is also achieved on transmissions. Opinions on gearboxes vary; those evaluators who still favor condemnation limits feel that success is quite low, while those who use trend analysis feel it is a little below 80%.

5.2 Chip Detectors

The chip detector is in bad repute among some Army personnel because of the substantial number of false alarms.* However, this problem is not by any means incurable, if the motivation exists. For purposes of discussion, the chip detector will be defined as the existing unit used on the UH-1, a simple magnetic plug with an electric sensor reporting in a YES/NO mode via a light on the instrument panel. Malfunctions have included chafed wire and water on the plug. The former could be alleviated by using a double wire rather than having the return circuit through the fuselage.

The capability of the chip detector is rather limited, since it attracts only ferrous metal particles of visible size. Viewed alone, this leaves a great deal to be desired, but as a supplement to ASOAP it has potential for filling the gap due to sudden fatigue failures, which was noted in 5.1. However, there is sufficient evidence of the value of detailed examination of the wear debris to merit turning at once to the more sophisticated devices in the next section.

5.3 Chip Collectors

For discussion purposes, a chip collector is defined as a device that retains relatively coarse wear debris, may report its status electrically in a more-or-less quantitative way, and can be opened for examination by the maintenance shop with a minimum of labor and oil spillage. The modes of collection have taken two different forms.

5.3.1 Magnetic Chip Collectors have proved themselves in service at British European Airways (1), which the British government has made into one

* McCullar, Col. F. M., USAAAVS, Fort Rucker, Letter of 7 January 1974.

47 Naval Air Systems Command, "Aeronautical Spectrometric Laboratory Manual," NARFP-P-12, (1 July 1972) and revisions.

of the world's largest short-haul airlines. They do not use a reporting collector, but pull the plugs on a 25- or 50-hour basis depending on engine type. The plugs, with debris untouched, are sent to a control unit where the debris is examined by microscope and the significance evaluated, in light of previous findings. These collectors are capable of attracting steel particles within the ASOAP range, though nonquantitatively. As an aid to this, the chips are taped to a file card and become part of the engine record. This procedure has been so successful that BEA does not consider SOAP would be worth adding to their program. This system has been imported to the U.S., along with the Rolls-Royce engines in the new 1011 Lockheed Aircraft, and the airlines must use it to meet guarantee requirements on the engines.*

Fort Rucker has worked out a very similar system** and applied it to their studies of CH-47 failures. The results have been quite good, and have raised their hits on the transmissions to about 98%. Details are given below in 5.9.

It is essential that the debris be examined by an experienced person. At Fort Rucker, this is done by the ASOAP Laboratory Chief. However, as discussed in Section 6, this could be done in a preliminary way at the shop and more completely at the laboratory.

Rather than depending on a time schedule as at BEA, Fort Rucker checks the plug electrically before pulling it. This appears desirable, and could be carried even further by using the device in Appendix D, which gives a quantitative reading of the amount of debris.

5.3.2 Filtration Collectors do not include the usual basket filter (36), which reports only when it is dangerously full. The newer devices (28) described in Appendix D use two or more electrical circuits to indicate 10%, 20%, etc., of the filter area covered with metal. These devices have the distinct advantage of collecting and reporting all kinds of metal, rather than being blind to nonferrous metal. However, they tend to pick up only the coarsest chips (250 μm and up) and so leave a wide gap in the size spectrum. They would appear to be most useful at the level of "final warning."

Like the magnetic collectors, the filter units can be pulled out and sent to the laboratory for further examination.

5.4 Light-Scattering Meters

The most tested of the new devices is a dual-beam meter which measures light absorption as well as scattering. This design avoids loss of sensitivity due to darkening of the oil, since the two signals are combined in a compensator.

These units were originally designed for in-flight use, but have

* Williams, L., personal interview at Delta Air Lines, Atlanta, Ga., October 19, 1973.

** Spano, E. F., personal interviews on January 15 and April 2, 1974.

recently been produced in a simplified model which could be used in the maintenance shop by semiskilled personnel.

The principle of operation is simply that each particle passing through the sensing zone is exposed to a fairly intense light beam, and the amount of light scattered at a 90° angle is reported. Perfectly clean oil gives a zero signal, and particulate contamination causes this to rise until a warning level is reached, similar to those used in ASOAP.

The limitations are inherent in the sensing method. In addition to being blind to the coarse chips, the light-scattering meter responds to organic matter, emulsified water and air bubbles. The reading, in fact, is based on the total cross-sectional area of all the foreign material in the light path.

The blindness to coarse chips is only the most obvious part of a general problem. Considering the nature of size distributions as displayed in Figures 14 and 15, there can never be a general correlation of light scattering with ASOAP. The light scatter depends on the area of particles; that is, the sum of the number of particles in each class interval times the square of the mean diameter in that interval. ASOAP depends on the weight of particles, which is proportional to the volume, and thus is the sum of the number of particles in each class interval.

Despite these criticisms on the scientific level, the light-scattering meters work out quite well at the engineering level. The reason for this paradox is that the ASOAP evaluators do not really work to any absolute standard. Instead, they have developed a set of practical standards for each major item on each class of aircraft. Even these are not used on an absolute basis, but rather on the basis of trend analysis as set forth in the Air Force manual (46). In other words, it does not matter that the spectrometer reads in ppm. If it read $\mu m^2/cm^3$, and the experience of the evaluators was in those units, the ASOAP program would function exactly as it does now, thanks to the nature of the log-square distribution.

The light-scattering meter could find a real place in the Army prognosis system, where quick decisions are needed and are subject to continued comparison with the more sophisticated ASOAP decisions.

5.5 Particle Counters

There are several particle counters on the market, all of which have been used for acceptance testing of new hydraulic fluids and preflight checking of rocket propellants. The best accepted of these (Appendix D) works by light scattering as in 5.4, but in a more sophisticated mode. The oil is passed through a narrow throat so that only one particle at a time reflects the light into a photocell. These signals go to a small pulse height analyzer, which sorts them into two or more channels.

The particle counter suffers from the same limitations as the light-scattering meter, and these can be overcome in exactly the same way.

Historically, the particle counter has been more difficult to calibrate than other monitors, but recent developments have removed this handicap.

5.6 Ferrograph Methods

A recent development which has received a good deal of attention from the Navy (13) is the Ferrograph. In its original form (8), now known as the Analytical Ferrograph, this device passes a small sample of oil over a glass slide placed over the pole-pieces of a high gradient magnet. This pulls out the iron and iron oxide particles, and displays them with the coarsest at the entry point, followed by a regular progression of smaller sizes. The slide is then examined in a special microscope under bichromatic illumination, which shows the metal as red and the oxide as green or yellow.

A simplified version for use in maintenance shops (1) followed. This is known as the Direct Reading and is described in some detail in Appendix D. A third version, known as the Real-Time Ferrograph, is now available for in-flight monitoring.

The two newer instruments differ from the analytical model in that they are equipped with photodensitometers at two points, representing coarse and fine particles. These readings, and especially their ratio, give a quick picture of the magnetic particle population and some insight as to the wear mode. Rolling fatigue, with its tendency to generate coarse particles by spallation, produces a significantly different ratio than abrasion.

Obviously, the Ferrograph is blind to nonmagnetic particles. However, it will collect paramagnetic material such as ferric oxide, and even nonferrous metals with steel specks.

5.7 Nucleonic Detector

Nucleonic Data Systems, Inc. (48) has developed a radioisotope excited X-ray fluorescence device for in-flight monitoring the metal content of the oil. It was given very little consideration in this study, as it appears to be even more speculative than the Ferrograph. However, the principle is sound (49) and the only question is how long it would take to design a version suitable for the maintenance shop.

5.8 Particle Detection by Shock Pulse

The SKF Shock Pulse Meter (MEPA) is an industrial device that measures pulses of mechanical energy emitted from a rolling element bearing load zone either when bearing surface damage is present or when particulate

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48 Bertin, M. C., "A Nucleonic Sensor for Detecting Metal in Recirculating Lubricating Oil Systems," USAAMRDL Report 72-38, September 1972, AD 752 580.

49 Beerbower, A., von Rosenberg, A. E., and Cross, N. O., "Radioisotopes," Encyclopedia of Chem. Tech. 17, 88-90, John Wiley and Sons, New York, 1968.

matter is encountered by the rolling elements (50).

The mechanism for generation of the shock pulse by the encounter of the rolling element with particulate matter is the conversion of a portion of the rolling element kinetic energy to the potential energy of the shock wave. Thus, whenever there are particles in the bearing raceways, pulses of mechanical energy are emitted from the bearing load zone. These shock pulses are sensed by a resonating accelerometer and an electronic signal analyzer tuned to this resonance. To sense the shocks requires only that this accelerometer be mounted in line with the bearing load zone from which shocks are emitted.

The shock pulse meter is in use in the United States mainly in a preventative maintenance role for bearings in industrial process machinery. Ten units are, however, in use by various military and space agencies for bearing condition monitoring and diagnostics on helicopters, rocket engines for Space Shuttle, environmental control systems on the Orbital Workshop (incoming inspection) and others.

The shock pulse meter has been successfully used by NASA Marshall to monitor contaminant levels in grease lubricated bearings installed in blower motors for a space application. Lubricant cleanliness can be quickly and quantitatively measured by the shock pulse levels and rates emitted by the bearing in operation. The tests preclude the installation of blowers having bearings with dirty lubricant which will shorten the bearing lives and make them noisy.

Field tests on UH-1 gearboxes have diagnosed the same kind of lubricant contaminant problems that subsequent teardown revealed to be due to wear particles from the bearing cages.

While the shock pulse meter primarily gives notification of bearing damage condition, these tests show that it also detects a precursor to damage, contaminated lubricant.

5.9 Microscopic Examination

Sizing, counting and identification of particles under the microscope are well established techniques in many industries. Specific applications to aerospace are described in ASTM Methods F 312 and F 314. Two Army laboratories have voluntarily developed their own methods to supplement ASOAP.

At Fort Rucker, an investigation was undertaken of the causes of FAILs in CH-47C transmissions. This required close cooperation between the ASOAP Laboratory and the organizational maintenance shop. When a transmission begins to show appreciable wear metal in the filters or chip detector, this debris is sent to the laboratory (unless an ASOAP warning had been given). This is an extension of the procedure for examining such debris in TM 55-1520-210-20, and is not related to the normal ASOAP samples. The

50 Howard, P. L., "Shock Pulse Instrumentation," Proceedings of Mechanical Failures Prevention Group 14th Meeting, 40-41 (1971) AD 721 355.

debris is redispersed in solvent and filtered out on a Millipore membrane, which is then washed, dried and examined under the microscope. First, a magnet is passed near the debris, and those which shift are classed as "magnetic." The remainder are classed as "nonmagnetic" metal, or "other."

The lengths of the largest magnetic and nonmagnetic particles are reported, along with a code for geometry (needle, chip, shaving, grain, fuzz) and number (excessive, medium, few, very few, none). Other particles are classed as "carbon," "sand" or "seal material," and the number of each is reported. Some results of this program on CH-47C transmissions are shown in Appendix B. While no statistical study has been made, all eight cases examined in this study would have been ASOAP FAILs had not microscopy made them all HITs. Of course, the MISS success was not affected from the 94% mentioned in 5.1.1.

The Fort Wolters ASOAP laboratory, now moved to Fort Hood, developed a somewhat similar program designed to reduce MISSs on the TH55 transmissions, and raise the success above the 83% noted in 5.1.1. In this case, the ASOAP sample was used. Part of it was diluted with pentane, and the magnetic particles were pulled out on the side of the container for separate examination. Size was not recorded. The success of ASOAP augmented by this test was 47/48, or 98%. Details are not included here due to phasing out the TH55A.

6. PROGNOSIS AND DIAGNOSIS

The tools that appear promising for detection on the basis of the discussions in the previous section are shown in Table 6. The next order of business is to determine which tools can be deployed, and in what manner, to provide the Army with a solution to the prognosis problem which is optimized for both safety and cost-effectiveness.

Numerous plans were formulated, considered and discarded. Rather than review the entire chain of reasoning and the reasons for the modifications, the sections below present a plan that has been discussed with a good many knowledgeable people and is responsive to most, if not all, of their objections. This does not imply that every person interviewed is in agreement, but merely that their suggestions have been accommodated as much as possible.

6.1 Definition of the Problem

Before starting to apply these tools, it will be necessary to consider the exact nature of the problems to be solved. The question to be answered is "What results would an ideal prognosis system give?" These can be listed, in approximate order of merit:

- Total freedom from FAILs.
- Instant response to an input (i.e., sample).
- Total freedom from MISSs.
- Minimum operating cost.

The reasons why each of these results has not been obtained in the past must next be analyzed.

6.1.1 The Causes of FAILs are partly identified by the last three wear modes in Table 5. These modes all produce large chips not accompanied by the small particles on which ASOAP depends (see Table B-5). From another viewpoint, these FAILs are caused by the definition of HITs (see 6.1) which excludes successful prediction by chip detector.

Communication problems are believed to result in some FAILs, though this is quite difficult to prove and statistics are totally unavailable. This would include samples not properly labelled, taken improperly from the aircraft, or not taken at all.

There is very little reason to attribute any FAILs to the spectrometers, which are highly praised by all evaluators who were interviewed.

6.1.2 Response Time is certainly not ideal in the Army system, especially at those laboratories receiving samples by mail. Nearly all results go out the day the sample is received, but samples that arrive at the post office in time for delivery Saturday cannot be processed until Monday. Samples received by mail average over three days from the time they are

Table 6. Tools for Prognosis

Method	Size Range Detected (µm)	Limitations
ASOAP	0.65 - 8	Blind to composition, size, shape
Magnetic Chip Collector	25 - 400+	Magnetic only
Chip Filter-Collector	400+	Coarse and conductive only
Light Scattering	0.1 - 8	Blind to composition, size, shape
Particle Counter	1 - 100+	Blind to composition
Ferrograph	1 - 20	Paramagnetic and ferromagnetic*
Shock Pulse	1 - 200	Size detected depends on particle hardness

*This includes very weakly magnetic, such as bronze plus a little iron.

taken from the aircraft until the response is received, and can run as much as eight days if the organizational maintenance people are not diligent in getting to the post office before the mailbag leaves.

6.1.3 The Causes of MISSs include a natural and proper concern about safety, which makes an evaluator tend to err on the conservative side. There is also a nearly complete lack of knowledge in the engineering profession as to just how long a machine can be safely operated after the first clear signal of abnormal wear.

Communication problems seem to cause more MISSs than FAILs, probably because of the evaluator's reluctance to endanger lives. When it is impossible to get a clear story from the organizational maintenance people, the only sensible compromise is to sacrifice costs rather than safety. Probably the worst deficiency is failure to report "time since oil change," with "time since new or overhauled" in second place. Without these data, trend analysis is nearly impossible. Another way communication can cause a MISS was found by scanning the records. The organizational maintenance apparently received the removal message twice. The first time they put a new engine on the aircraft, and the next time removed that engine and sent it in for diagnostic inspection.

6.1.4 High Costs in the ASOAP laboratories have not been a major problem in the Army, since they use fewer laboratories than the Navy or Air Force. The cost of MISSs is probably higher than for the Air Force but appears lower than that of the Navy. One clearly identifiable high cost item is the excessive number of false alarms on chip detectors (see 5.2). This could be considered a special kind of communication problem, of machine to pilot.

The cost of FAILs cannot be estimated for lack of data. Even more complex is the cost of premature HITs, which appear to be causing a good deal of excessive costs at the depot maintenance shop level.

6.2 The Evidence in the Debris

As shown above, there is much more evidence in the wear debris than has ever been used. This may be summarized into the following characteristics:

a - Concentration in the oil
b - Rate of change of concentration
c - Principal and other metals
d - Ratios of metals
e - Chemical form (metal, oxide, metallo-organic)
f - Particle size distribution
g - Particle shape

Attempting to use all of these facts for prognosis would be both confusing and very expensive. Thus, the ideal prognosis system of Section 6.1 must be selective. This raises these questions:

- What would be the most efficient kinds of evidence to prevent MISSs and FAILs due to technical causes?

- What means of collecting and disseminating this evidence would most closely approach "instant response" without incurring the waste due to excessive haste?

6.2.1 S all Particle Evidence used in the ASOAP system includes characteristics a, b, c and sometimes d. This has certainly gone a long way towards the goal and should not be given up unless something much better can be found. There are, of course, alternative methods for sifting this evidence.

6.2.2 Chip Evidence is the heart of the present organizational level prognosis. This extends down to perhaps 20 um on magnetic "fuzz" and 40 μm on all kinds of particles. This evidence has shown its value at BEA (1) and Fort Rucker, as well as many other places, but the Army in general has not yet optimized its use. This could well include characteristics a, b, c, e, f and g, but at present leans only to b, c and f.

6.2.3 Chemical Form is the clue to corrosion and is presently examined only by the cumbersome drain procedure (see 5.1). With the low flying hour schedules of peacetime, better use of this evidence may become crucial.

6.2.4 Collection and Dissemination by ASOAP system has been slow enough to attract criticism. The organizational level system appears fast enough to satisfy everyone. Though there is room for question on the present technical precision, this system appears to offer a highly optimized solution to communication problems.

6.3 The Time Scale in Prognosis

A third question, not raised in Section 6.2, is much more basic. Given perfect collection and dissemination of evidence, how good a prognosis could be made? The only fair way to answer that is with another question: What constitutes a good prognosis, within the definition on page 9? The progress of a disease is seldom predictable enough to support much confidence in long-range numerical prognostic statements, especially those made when the symptoms are first detected. Prognosis becomes more reliable as the time scale is shortened, either by asking short-range questions or by impending death. The same should be true of wear processes.

There are several key points in the life of an engine, transmission or gearbox, in terms of time since new or overhauled:

- First detection of wear debris trend,
- Propagation of damage to most of the moving parts, and
- Unit no longer operable.

Another key concept, which is much less easy to define, is the time at which safety is no longer acceptable. ASOAP tends to put this close behind

the detection point, and the Navy appears to have a very similar policy. The Air Force evidently allows more wear (see 5.1).

The three key points all require different forms of prognosis:

6.3.1 First Detection could be predicted by actuarial statistics, as discussed by Dougherty (27). The means of setting the TBO for engines, etc., must also depend, directly or otherwise, on actuarial experience. The "book values" for rolling element bearings (15) are the best example of this. However, the Air Force and most commercial airlines prefer to eliminate TBO and make their overhauls on SOAP data (1).

6.3.2 Propagation of Damage is a very different matter, as no "book values" exist for this phenomenon. In fact, there is no real mathematical model for the wear rate of a rolling element bearing after the first spall (28). Gear predictions are in no better condition (23). Experimenters tend to stop their tests when the element has "failed," regardless of the fact that users tend to continue running for many more hours. For this reason, not even perfect diagnostic ability would permit predicting the rate at which debris from one spalled ball or roller would damage the rest of the set. Undoubtedly, this would depend partly on the rest of the system, and on the filtration in particular (see 2.3.3).

Prognosis of the rate of propagation of failure through a transmission would appear to be hopeless in view of the preceding paragraph. However, actuarial statistics are much more easily applied to large than to small populations, if the experience is available. As pointed out by Steiger (39), the Weibull plot provides a convenient method for such cases. The case most readily at hand was that of CH-47 transmissions. Taking all the units for which ASOAP records from AAVSCOM and diagnostic teardown reports from Boeing Vertol were available gave 34 transmissions. This required pooling all the various transmissions on the A, B and C models, and yielded 34 case histories. From these, the "critical" gears and bearings (excluding those which never became damaged, as well as all structural parts) were selected. Of the case histories, only 15 met the requirements of including full ASOAP records from earliest indication to removal, and diagnostic teardown records of all parts replaced. All 15 were HITs.

The transmissions were tabulated in ascending order of the number of hours flown after the first ASOAP indication, along with the number of critical parts in each (Table B-6). There were 172 critical parts. Each removal was then computed as the percentage of the critical parts damaged out of those still available, censoring out all the critical parts in each transmission after its data were used. The percentages were then plotted into Figure 72, yielding quite a good straight line. The L_{50} of 52 hours is in striking agreement with the engineering opinion of "50 hours or more" cited in 3.11.

This does not provide any measure of safety. It must be emphasized that all these aircraft were still flying, though the one with 99% of the critical parts damaged at 141 hours must have been rather shaky. The

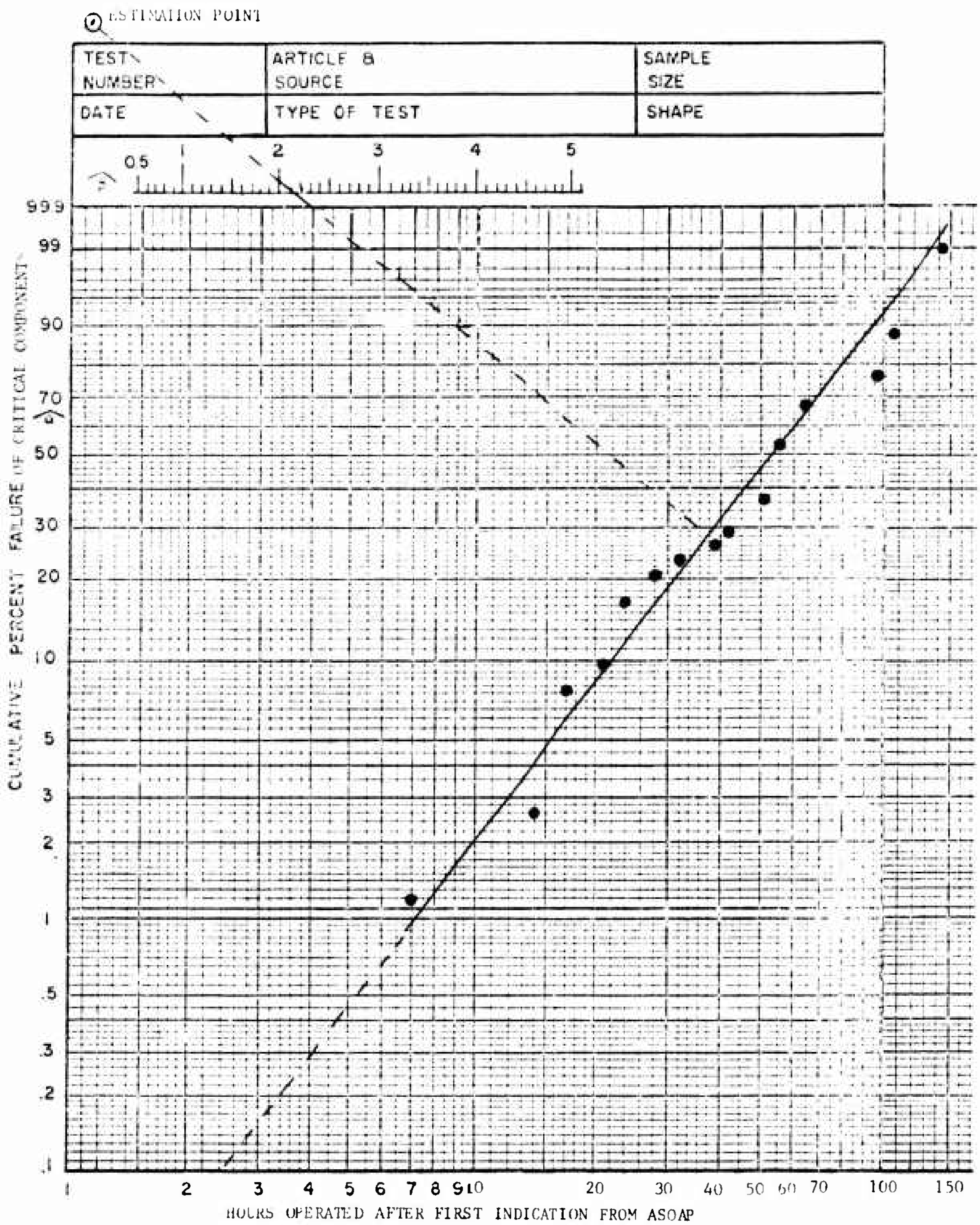

Figure 42. Weibull Probability Chart for CH-47 Transmission Gears and Bearings.

question that can be addressed by Figure 42 is an economic one -- is it cheaper to replace a single critical part at the first indication, to wait 52 hours and replace 50%, or wait 141 hours and replace everything?

Though it may be too obvious to require stating, Figure 42 can be used only for CH-47 transmissions. Had the study item been the T-34 transmission of ten years ago, the slope would have been much steeper since the dominant failure modes then were subsurface impurities in the steel, and a sleeve bearing. Both resulted in sudden failures, which have been practically eliminated in the CH-47. No doubt the data will eventually be assembled, making it possible to prepare Weibull plots, on the UH-1 transmission and gearboxes, as well as the various engines.

6.3.3 Testing to Destruction has not been very popular in the aircraft industry. The sole exception has been fire testing, of which the Eustis Directorate has done a large share. However, there are no applicable data to prognose the future of power train components beyond the end of Figure 42. It can only be said that until such tests are made, there will be no fully realistic way to estimate the safety of flying beyond the first ASOAP warning. A brief plan for conducting such tests on a minimum cost basis is discussed in Section 8.

6.3.4 Cost Control is always in competition with safety, and the above discussion carefully avoided taking sides. However, this leaves untouched the problem of overall cost effectiveness. It seems quite evident from Figure 42 that removals at the first ASOAP warning are premature. Since it was not possible to include FAILs in that study, there is every reason to believe that taking the full 141 hours would produce some accidents. As a working goal, it would seem that the combination of the engineering opinion of 50 hours with the L_{50} life of 52 hours could be expected to provide an acceptable balance until facts are available to change it.

6.4 Prognosis by the Pilot

While it is not explicitly shown in Table 6, every prognosis tool there (except ASOAP) has the capability of providing in-flight signals to the pilot. Recognizing that between three (OH-6) and six (CH-47) major items could be fitted with two (or more) prognosis tools each, the technical facilities are available to keep the pilot informed on most of the potential problems shown in Table 5. Whether this would be desirable is another matter entirely.

The contractor is obligated to "evaluate and compare the use of continuous (in-line) monitoring/analysis with intermittent (on-ground) monitoring/analysis." This is not entirely an engineering problem, as it raises questions of the pilot's ability to process such a mass of data in a useful way. Suitable advice was sought, and the concensus was that the pilot is already nearly saturated with information. The best example is a program at the Naval Air Propulsion Test Center* which is aimed at computer screening the data supplied to the pilot, so that only the "Seriously Off-Condition"

* Piscopo, P., personal interview at NAPTC, Trenton, N.J. on January 29, 1974.

signals reach him. This sort of device appears feasible for aircraft of the future, but retro-fitting the thousands of existing Army helicopters is not worth considering.

Anotner important question concerns the Army pilot's need for such information. Considering that his average mission goes less than 1 hour, and that he can carry fuel for at most 2 hours, any in-flight prognosis with more range than that is of little value to him. Another important factor was raised by Rummel,* who has collected evidence showing that more accidents are caused by needless precautionary landings than could possibly result from flying on bearings in the early stages of spallation.

The result of this analysis is shown in Table 7, and amounts to giving the pilot exactly what he already has. The oil temperatures and pressures on engines are, of course, what everyone depends on in car, plane or boat. The same readings on the transmissions are also vitally useful, especially when enemy gunfire is encountered. The only change is one of which the pilot will hardly be aware, exchanging the chip detector for a chip collector, which will be examined at the organizational maintenance shop. Temperature sensing has proved too slow, or useless if the oil is lost, and there is no forced circulation to provide a pressure. An exception is on the Navy CH-53, which is used on relatively very long missions with in-flight refueling.

Table 7. What The Pilot Needs To Know

Prognosis = 1/2 to 2 hrs.
Diagnosis = none

	Engine	Transmission	Gearbox
Oil Pressure	+	+	-
Oil Temperature	+	+	-
Chip Collector	-	-	-

6.5 Prognosis at the Organizational Level

The crew at the organizational maintenance shop already play a considerable role in prognosis by ASOAP, though this is often overlooked by those more concerned with spectrometer precision, etc. This includes taking the oil samples, a step so vital that both the Navy (47) and Air Force (46) have provided very detailed instructions. They are also responsible for carrying out ASOAP Laboratory instructions for the corrosion check described in Section 5.1, or other special handling of aircraft with equivocal readings. They also perform other prognosis functions, though these seldom are given such a dignified title, and render decisions on airworthiness which are essentially binding on higher ranking personnel.

It appears highly desirable that the maintenance shop be equipped to make a preliminary evaluation of fine particle content, using the ASOAP

** Rummel, K. G., personal interview at Boeing Vertol on April 11, 1974.

samples. This would permit rendering a decision within a few minutes. It would require installing one of the fine particle meters from Table 6 at each such shop. It appears that the light scattering device, the particle counter, the shock pulse meter, and the Direct Reading Ferrograph are all good candidates. It would be necessary to establish decision procedures for the instrument selected which would be similar to but independent of the ASOAP program, just as the Air Force has separate criteria for the emission and atomic absorption spectrometers.

As shown in Table 8, the shop crew could make two kinds of decisions (in addition to the "all clear"). The "High" reading calls for grounding the aircraft, while the "Medium" reading merely calls for 5 hour surveillance. The fine particle meter decisions should be made on a trend basis, if possible, with the educational level of personnel available. If this proves impractical, condemnation limits would be used, as would always be true on chips.

Table 8. Readings Needed at Organizational Level

Prognosis = 25 to 50 hrs.
(Based on change from last record)
Diagnosis = Limited

Readings	High	Medium
Fine Particle Meter	Component to Depot Maintenance*	Drain and flush sample in 5 hrs.
Chip Collector	Component to Depot Maintenance*	Query every 5 hrs.
Filter Contents	Component to Depot Maintenance*	Inspect every 5 hrs.

* Subject to confirmation by ASOAP Laboratory.

The remainder of the sample would be forwarded to the ASOAP Laboratory, just as at present. However, the purpose would be to maintain constant checking and on-the-job training of the shop crew, under the surveillance of the ASOAP Laboratory Chief. For this reason, copies of the shop data must accompany the samples.

The component would not be removed from the aircraft until this decision was confirmed by the ASOAP Laboratory. Thus, if the shop made a mistake on the overcautious side, the only loss would be a few days of availability. On the other hand, a mistake on the undercautious side would let the aircraft fly until grounded by the ASOAP Laboratory, just as at present.

The second part of this plan would require retrofitting the aircraft with chip collectors on all major items, to replace the present crude detectors. The maintenance shop would be equipped to query each collector

every 25 hours. On new aircraft, this could be done by connecting a multi-pronged plug to a socket on the aircraft, but on existing units individual connections to a portable meter, or even simply manual removal for inspection, could be made. If the meter goes over the acceptable limit, the collector would be pulled and inspected. If a filter type chip collector is not used, the ordinary filters would also be inspected at this time, and also at predetermined intervals.

The shop crew would, as on the oil sample, make a preliminary decision and send the chips to the ASOAP Laboratory. The same rules would apply as on fine particles. The present TM 55-1520-210-20 provides some illustrations of fuzz and chips on plugs, but these need to be made clearer.

If retrofit is undertaken, this should include consideration of taps to make taking oil samples properly easier than taking them improperly (1).

6.6 Prognosis at the ASOAP Laboratory

The increased activity at the organizational level maintenance shops would mean some change in the role of the ASOAP Laboratories. This could be an increase, rather than a decrease, in workload and responsibility. The flow of oil samples would continue at exactly the present level, except perhaps that some shop crews might want to be reassured and send more 5-hour samples at first. Later on, there might be less samples. If this proposed plan is as reliable as appears likely, the routine sample period for ASOAP analysis might be extended beyond 25 hours.

The Laboratories have always kept in close contact with the shops, and this would continue, but in the role of teacher, consultant and court of appeals. Due to turnover in the shops, the stability of the proposed system must depend on the Laboratories.

Additional duties are indicated in Table 9. The use of the particle counter as an aid to prognosis would be an option, not a routine duty. It would depend on the plan proposed by AAVSCOM (51) to put hydraulic fluids on particle count control, which would make counters available.

Examination of the chips would be along the lines practiced at BEA, and Fort Rucker. This would again be in close cooperation with the maintenance shops.

The degree of success anticipated is shown in the right-hand column of Table 9. The ASOAP figure is based on engines, mainly Air Force and commercial airlines. The particle counter value is based, very conservatively, on experience with hydraulic fluids. The 80% for chip collector examination is also very conservative, based on BEA.

These values can be combined to yield a rough estimate of the success to be anticipated. However, it is necessary to handle them as failure

51 Librach, D., Minutes of Laboratory Chiefs Conference, Lexington, Ky., April 2-3, 1974.

Table 9. Measurements at ASOAP Laboratory

Method	Procedure	Purpose	Anticipated Success
ASOAP	As at present	Provide final prognosis to prove preliminary findings at Maintenance Shop.	80%
Microscope	As at Fort Rucker	Provide verification (or education) to Maintenance Shop, and appropriate guidance to Depot Maintenance.	80%
Particle Counter	As on hydraulic fluids	Provide supporting evidence for ASOAP prognosis by checking which metal is solid or in solution. Use only on samples on which there exists some serious question.	50%

rates. On this basis, if ASOAP fails 20% of the time, the counter will catch 50%, leaving 10%; chip examination would let 20% of these past, for a failure rate of 2% or a success rate of 98%.

6.7 Diagnosis as an Auxiliary Value

While the emphasis of this study has been on prognosis, it has not been possible to ignore completely the diagnostic aspects. These could arise at three levels.

6.7.1 Reduction of FAILs through microscopic examination of the chips is essentially diagnostic in nature, though the results are immediately used for prognosis.

6.7.2 Reduced Costs per overhaul at depot maintenance, or any other overhaul shop, do not appear to be a realistic goal. If a bearing (or gear) has started to spall anywhere in a major item, limiting the teardown to the components flagged by the maintenance shop and ASOAP Laboratory would seem to be a rather extraordinary form of false economy.

6.7.3 Improved Knowledge due to improved diagnosis is another matter. Since one avowed purpose of diagnostic teardown is engineering improvement recommendations (EIR), the careful examination of chips at the laboratory should have some distinct value.

6.8 Information Loops

To clarify further the proposed plan, see Figure 43. The diagram is essentially self-explanatory, and is merely a visualization of what has been found to be the operational mode surrounding several very successful ASOAP operations. The proposed plan would not change the pattern, but merely shift the burden of making the preliminary decision to the most central possible position.

One point on Figure 43 that needs to be emphasized is the need for continued feedback from depot maintenance or whatever overhaul facility is used. In the past, many shop records have not reached the ASOAP laboratory chiefs. Some units have been overhauled in Army shops, and others at the manufacturers shops. The latter advised that they were not funded to provide detailed reports. When such reports were sent in to AAVSCOM, funding and/or manpower was not available to key punch them into card form. As a result, most of the 1972-3 records are imcomplete and it was only through the courtesy of the Boeing-Vertol engineers that some parts of this period could be analyzed.

At present, ARADMAC is funded to do diagnostic teardowns on all ASOAP related removals. However, this is not a permanent arrangement and the system may soon revert to the old mode, or even worse with overly austere funding. If prognosis is to even maintain the present level, let alone be improved, it is essential that the bottom loop on Figure 43 be kept functional by whatever means are appropriate.

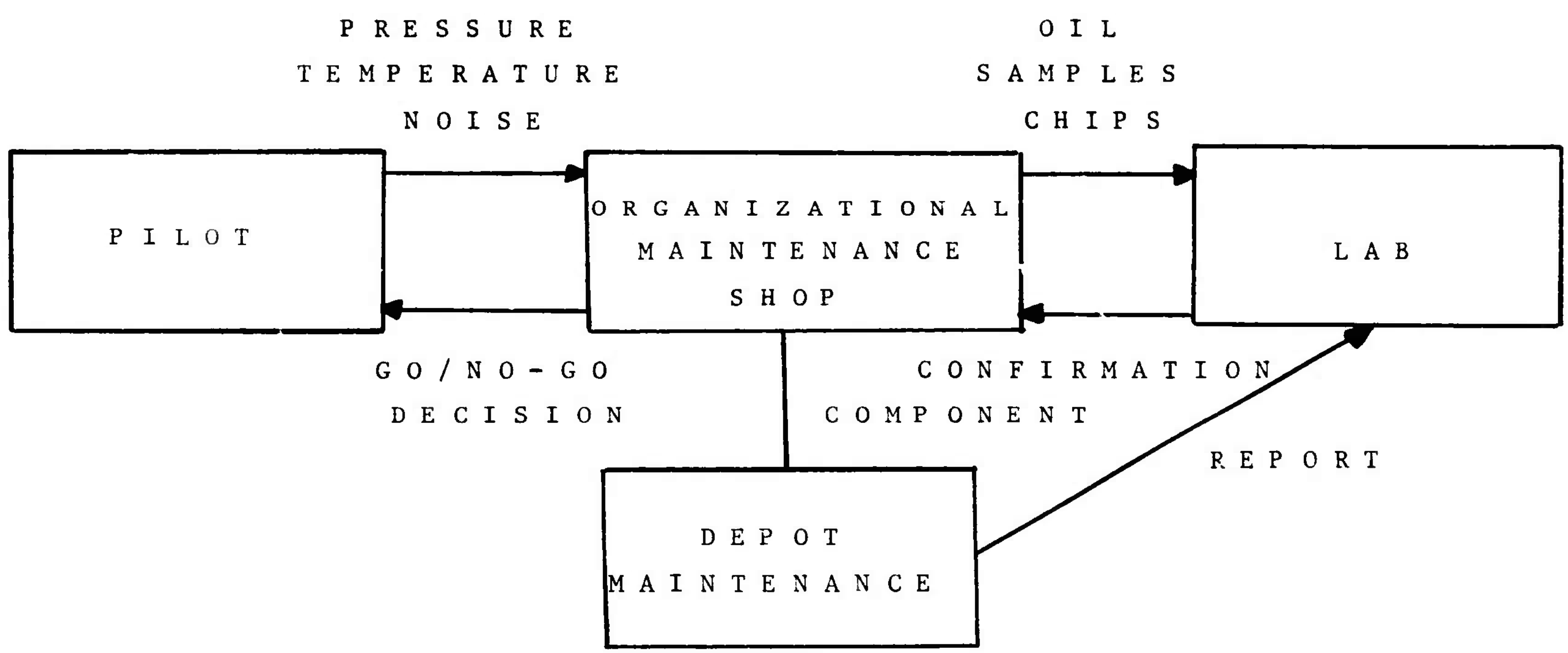

Figure 43. Information Loops.

7. TYPES OF AIRCRAFT CONSIDERED

The Army operates a substantial number of six classes of helicopters, and to study each would have spread the effort so thin as to be ineffective. Instead, the precedent set by Bowen (26) was followed, and only two classes were examined in depth.

7.1 The UH-1 has been the largest class and a great deal of data has been built up on its characteristics. Hence, it was the first choice for study. The AH-1 uses the same power train and can be considered to be the same except for nonoil-wetted parts.

The OH-6 and OH-58 are not as close to the UH-1, but we were advised that they present no special problems. Careful study of the AAVSCOM reports (too numerous to list) indicated this to be accurate. Any differences found took the form of the OH classes being simpler than the UH-1.

7.2 The CH-47 presents unique problems and was the other aircraft chosen by Bowen for study. Actually, there are enough differences among the CH-47A, B and C to necessitate some care in mingling the results. In addition to the AAVSCOM-provided reports, the engineers at Boeing Vertol were most helpful in providing information (Appendixes B and C).

7.3 The CH-54 is used in limited numbers, and the AAVSCOM reports did not indicate any special problems. After discussion with the Project Manager, it was decided to omit any study on this aircraft.

7.4 Future Problems

7.4.1 The UTTAS was selected as a future aircraft which may bring new problems in prognosis. However, the only problem encountered is the plan to equip the UTTAS with the T-700 turbine engine, containing 3 μm filters. This will definitely require increased use of chip collectors for prognosis, since these filters remove much of the debris needed for the ASOAP method.

7.4.2 Grease Lubrication (52,53), if adopted, would require rethinking the entire prognosis concept because MIL-G-83363 does not circulate freely, and it is nearly impossible to obtain a meaningful sample. Chip collectors would not work either, so that some sort of acoustic signature or shock pulse meter (AIDAPS or MEPA) would be required.

7.4.3 Microfog Lubrication (32), on the other hand, could be very readily monitored by mounting a chip collector on the exit airstream from the transmission.

52 Christian, J. B., and Simmons, B. R., "Grease Lubrication of Helicopter Transmissions." Lubr. Eng. 30, No. 7, 340-350 (1974).

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8. RECOMMENDATIONS FOR EVALUATION

The plan proposed in Section 6 is obviously not the sort of action the Army would take without making a stepwise evaluation of the costs, benefits and difficulties involved. The following steps are suggested for obtaining those answers in a cost-effective manner.

8.1 Scale of Testing

In view of the low peacetime flying schedule, a sizeable number of aircraft should be involved. However, the present austere basis of funding sets an upper limit. It appears that the test should be conducted at a single base where these criteria could be met:

8.1.1 Good ASOAP service, on-base or readily accessible.

8.1.2 Diagnostic teardown facilities.

8.1.3 About 120 aircraft, all of the same class and with similar histories. Using 60 for the test group and 60 for a control group, at about 25 flying hours per month, would give about 18,000 hours per year, with three major inspections per aircraft.

8.2 Fine Particle Detector

The first step would be to fit up the maintenance shops for the 60 test aircraft with fine particle detectors. This would involve three shops for the UH-1, or seven for the CH-47. It would be possible to compare the four types of detectors, but a much better statistical basis would result from preselecting one type on grounds of simplicity of operation, rugged design and cost.

Some care should be taken to avoid an unrealistic high level of training at the shops, for the obvious reasons.

8.3 Chip Collectors

It would be necessary to fit up the 60 test aircraft with chip collectors. In this case, both the magnetic and filtration type could be tested without loss of statistical precision, because the test aircraft would carry at least 120 of each type.

8.4 Laboratory Facilities

If not already available, the laboratory would have to procure a microscope of at least 100X power. It would also be highly desirable to have a 5-channel particle counter, as specified in MIL-H-5606 (51).

8.5 Procedure

The test engineer should be as inconspicuous as possible, since

the factors being evaluated are partly psychological. The results would be compiled and given statistical analysis in an impersonal manner, preferably by someone without other involvement.

8.6 Testing to Destruction

As an option, to be exercised if at all possible, a statistically significant number of these aircraft should be run to failure of the power train. This would be accomplished by taking some which have completed the above program and had the resulting damage diagnosed but not repaired. These would then be put on cyclic tiedown running, until completely inoperable. They would then be torn down and every damage mode reported for safety hazard evaluation.

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APPENDIX A

GLOSSARY OF DETAIL FAILURE ANALYSIS SHEET BASED ON BOWEN'S REPORT (26)

1. GEAR TOOTH OR SPLINE

1.1 Wear

1.1.1 Destructive Wear

Destructive wear is wear which has resulted in a major change in the involute shape of the gear tooth. Destructive wear would be accompanied by extremely rough operations, nonuniform motion, and shock overloads which would probably result in tooth breakage.

1.1.2 Abrasive Wear

Under normal circumstances of lubrication, the occurrence of abrasive wear would be extremely infrequent. If the inclusion of sand and water in appreciable quantities should occur, abrasive wear may be observed. Fully case-hardened gears are not likely to exhibit any significant abrasive wear. Medium hard and soft gears will frequently exhibit this type of wear.

1.1.3 Galling

Galling is a form of contact welding which results in the transfer of material from one gear member to another. It is quite infrequent in moderate to high-speed gearing, but is often seen in low-speed and stop-start type operations.

1.1.4 Scoring

This type of wear is often referred to as "scuffing" and is evidenced by radial wear lines superimposed on a roughened thin layer of melted material. Bright shiny wear on black oxided gear teeth must not be confused with true scoring. This condition,though considered normal for many applications,represents a lubrication state intermediate between thick film asperity separation and film failure conditions associated with scoring.

1.1.5 Frosting

The term frosting will be limited in usage to fully hardened gear tooth profiles. It shall be used to define the existence of a large number of small round or elliptical patches which under high magnification exhibit the general appearance of minute scoring occurrences.

1.1.6 Corrosive Wear

This term should not be used to define the existence of ordinary oxidation corrosion which is cause for replacement of the component. True corrosive wear occurs most generally in over-temperature operations in the presence of extremely strong EP additive

lubricant of the chlorine or sulfur families and therefore will be an infrequent occurrence. It can also arise from oxygen dissolved in the oil (see 2.5.3 and 3.4.3).

1.1.7 Interference Wear

Interference wear does not occur in correctly designed, properly operating gear sets. Interference wear defines the effects of the tip of one gear tooth member contacting the fillet or root area of its mating gear tooth. If this occurs in the helicopter transmission, it will probably be accompanied by an extreme over-temperature condition or an unusual type of support bearing failure which reduces the operating clearance or backlash of the gear set.

1.1.8 Burning

Burning indicates surface tempering or softening of the tooth member. It will most probably be accompanied by a total loss of lubricant. Scoring, destructive wear, and tooth breakage may also be present. In general, burning is an advanced condition of the following term.

1.1.9 Discoloration

This term is used to locate the existence of surface temper coloring of either the active profile, the top land, or the coast side of the gear tooth. There is generally no appreciable softening of the metal to any significant depth. The condition may be indicative of marginal lubrication or excessive power operations.

1.1.10 Misalignment

Misalignment indicates operation of the gear or spline set at axes skewed from those intended by the designer. When this term is checked, at least one other term must also be checked to explain the physical result of the indicated misalignment.

1.1.11 Surface Treatment Worn Through

This term implies that the gear or spline in question was treated with an antiwear surface coating such as Electro-Film, Dicronite, or in some instances, soft metal plating.

1.1.12 Oil Absent

This term indicates the partial or complete failure of the lubrication system either in the immediate area of concern or in the entire transmission.

1.1.13 Corrosion - Other

This term is used to define the existence of ordinary oxidation corrosion which is cause for replacement of the component. This may occur during helicopter nonoperation intervals under severe moisture conditions or occur in transit, storage, or handling due to improper preservation.

1.2 Surface Contact Fatigue

1.2.1 Destructive Pitting

Destructive pitting shall be used to define the existence of advanced state of tooth profile deterioration. This term is used without concern as to the origin or generic identification of its beginning. It further indicates that complete loss of function of the gear tooth is imminent.

1.2.2 Spalling - Fan Shape

This term shall be used to define a pitting condition whose origin can be physically detected at the apex of the fan shape portion of the damaged area. This is a surface initiated type of fatigue which has its origin in the surface tensile cracking which leads to the gradual erosion and exfoliation of increasingly larger pieces of gear material as the fan widens out in the direction of sliding action. The cracks will ultimately undermine the entire case of case-hardened gear teeth as the spalling approaches the extremities of the addendum.

1.2.3 Arrested Pitting

This term shall be used to indicate the existence of very small shallow pits which are not propagating into larger failure areas. A good example of this frequently occurs in the flank of the planet pinions in contact with the nitrided ring gears. This type of pitting has also been observed on spiral bevel gears and is frequently associated with the waviness condition referred to as "barber pole." This pitting is often considered to be corrective in that it progresses immediately to the point of relieving local compressive stress of over-load.

1.2.4 Pitch Line Pitting

Pitch line pitting belongs to the family of rolling contact fatigue. It is not generally associated with a condition of lubrication distress but generally occurs at relatively high cycles of loading. In fully hardened, properly designed gears, it seldom is seen in less than 100,000,000 cycles of operation.

1.2.5 Addendum Origin

Checking this term merely signifies the site of origin of one of the above types of pitting or spalling.

1.2.6 Dedendum Origin

Checking this term merely signifies the site of origin of one of the above types of pitting or spalling.

1.2.7 Case Crushing

Case crushing means shear failure of the core-case interface in case-hardened gear teeth. Generally, insufficient case depth for the load magnitude is indicated. Multiple cracking, often both transverse and longitudinal, is generally observed in the tooth face.

1.3 Breakage

1.3.1 Fatigue
Fatigue shall be used to define high-cycle repeating stress failure with a fracture surface being well defined with the customary clam shell or bench marks. Unless otherwise defined, it shall be assumed that the failure origin is in the root fillet area of the gear tooth.

1.3.2 Wear
This term should not be used alone in the breakage category but merely serve as a modifier to indicate that some other form of breakage was accelerated by the presence of wear.

1.3.3 Overload
In the instance of properly manufactured gears, the occurrence of overload breakage is evidenced by low-cycle fatigue with few, if any, bench marks. The failure interface may in fact resemble the crystalline appearance of a static failure.

1.3.4 Misalignment
Misalignment is operation with skewed axes, which results in a particular form of breakage defined elsewhere in this category.

1.3.5 Quench Cracks
Quench cracks which occur at or near the interface of the core-case structure and result from either excessive case depth or improper location of the part relative to the quenching dies during the hardening process.

1.3.6 Grind Cracks
Grinding cracks result from excessive temperature between the wheel and tooth interfaces during manufacture, which induces a tensile stress field in excess of the elastic properties of the material. This type of crack is generally found to occur orthogonally to the direction of the grind wheel passage.

1.3.7 Impact
Impact breakage shall be that which results from sudden stoppage or debris in mesh. It will be a completely static fracture and will be accompanied by extreme deformation of the failed tooth in all cases except static fractures in nitrided gears.

1.4 Debris in Mesh

1.4.1 Moderate Damage
Moderate damage shall be defined as that level of damage which does not impair the basic functional operation of the gear tooth.

1.4.2 Heavy Damage
Heavy damage shall be defined as that level of damage which impairs the basic functional operation of the gear tooth and leads to catastrophic failure of the gear.

2. BEARINGS

2.1 Spalling (Figures 24,25,26)
This term shall be used to define a flaking condition whose origin may be of the classical subsurface fatigue mode or a surface initiated type of fatigue.

2.2 Surface Distress (Figures 27,28,29,30)
Sometimes described as glazing and micropitting. This term shall be used to indicate the existence of very small, shallow pits which are not propagating into larger failure areas.

2.3 Corrosion (Figures 36,37,38)
This term is used to define the existence of ordinary oxidation corrosion which is cause for replacement of the component. This may occur during nonoperation intervals under severe moisture conditions with or without the presence of highly contaminated oil.

2.4 Dented (Figure 18)
Dents (indentations) in the raceway occur when foreign particles are introduced into the bearing and are pressed between the rolling elements and the rings. Item 2.5 or Item 2.6 should be marked in conjunction with this failure mode. Denting is not to be confused with brinelling, which is explained in Item 2.13 below.

2.5 External Debris
This indicates that the debris which caused bearing damage did not originate from the bearing itself, but from another (external) failed or damaged part.

2.6 Internal Debris
This indicates that the debris which caused bearing damage originated within the subject bearing. For example, debris from inner race failure causing damage to the outer race.

2.7 Broken
This term is used to define the condition where the bearing element is fractured completely through the element cross-section. Additional information will usually be required in the Summary and Remarks section.

2.8 Cracked

2.8.1 Grind Cracks
Grinding cracks result from excessive temperature between the wheel and bearing element interfaces during manufacture, which induces a tensile stress field in excess of the elastic properties of the material. This type of crack is generally found to occur orthogonally to the direction of the grind wheel passage.

2.8.2 Rubbing Cracks
If a hardened bearing ring under rotation rubs against a stationary part, rubbing cracks may develop. These cracks always run

perpendicular to the direction of rubbing.

2.8.3 Defective Material Cracks

Cracks caused by defective material ordinarily have an easily recognizable character, but their actual cause can often be determined only by metallurgical investigation. Any failure by cracking will require further explanation in the Summary and Remarks section.

2.9 Smearing (Figures 32,33,34,35)

Smearing occurs at predominantly sliding contacts, such as on roller ends or cages or because of rolling element skidding in the absence of sufficiently viscous lubrication. Smearing, as the name implies, is evidenced by a smeared-appearance deterioration of the raceway or contact surface.

2.10 Glazing

This is the initial stage of surface distress described in Item 2.2, whereby the affected area on the raceway becomes shiny in appearance, similar to the finish on a new ball. Metal flow has taken place during this mode of failure.

2.11 Wear

This is the deterioration of the bearing rolling surfaces through normal usage. Abrasives in the lubricant and/or poor lubrication accelerate the wear process.

2.12 Grooved (Figure 31)

Continuous circumferential indentation on balls produced by balls running on retaining diameter of counterbored raceway.

2.13 Brinelled

Brinelled is a term applied to a bearing which has been statically loaded to an extent such that the raceways and rolling elements are permanently deformed. A brinelled bearing has indentations in the raceways and often has corresponding flats on the rolling elements.

2.14 Fretting (Figures 39,40)

Fretting is generally considered to be a corrosive form of wear caused by very slight movement between two metal surfaces under very high contact pressure. The formation of an iron-oxide paste between two fretting steel members is not uncommon. It is often seen between the inner ring and the shaft or outer ring and housing. Fretting wear marks in raceways of stationary bearings subjected to vibration is called "false brinelling."

2.15 Creeping

Creep is relative movement between the bearing inner ring and the shaft, caused by inadequate interference fit for the applied load. Creep causes not only undesirable ring wear but also excessive shaft wear. Creep is evidenced by circumferential scoring on the bearing bore and shaft. It may be an advanced stage of fretting.

2.16 Spinning

Spinning is an advanced stage of creep. The relative movement between inner ring and shaft is much greater than in creep, and the sliding surfaces may become polished. The iron-oxide from the fretting phase may still be present and assist in further wear.

2.17 Incorrect Installation

This term will be used when the bearing has obviously been damaged at installation or has been installed incorrectly. A common example is forcing an assembled roller bearing over the inner race with the rollers misaligned, causing marks (smeared streaks) on the inner race.

2.18 Disassembly Damage

This term will be used when the bearing was damaged at disassembly.

2.19 Discolored due to Temperature

Discoloration of bearing elements indicates operation with marginal lubrication or at excessive power conditions.

2.20 Scratching

Scratch marks, usually on balls or rollers, due to abrasive marking by debris such as that trapped in the cage pockets.

APPENDIX B

DATA BASE

This appendix contains excerpts from reference material to back up some of the conclusions drawn. It is not designed for easy reading.

Table B-1 is Bowen's (26) Table III on the UH-1 transmission. A misprint has been corrected on Item No. 25, Quantity Replaced, from 25 to 3.

Table B-2 is Dougherty's (29) Table XL on the CH-47 transmissions.

Table B-3 is a condensation of Short's (45) report. The category "Fixed Wing" includes a great many kinds of fixed-wing aircraft and associated engines, both turbine and reciprocating.

Table B-4 is a condensation of the U.S. Air Force data on helicopters, for the calendar year 1973.

Table B-5 summarizes microscopy data from Fort Rucker on the CH-47C. Figure B-1 shows the same data in Weibull plot form.

Table B-6 shows the data on CH-47 critical parts replacement used in Figure 42.

Table B-1. Parts Replaced - Bell Transmission

Item No.	Part Number	Part Name	Quantity Replaced	Quantity Per Trans.	% Replacement	Quantity Primary Failures	% Primary Failures
1	204-040-103-7	Gear, Spiral Bevel, Tail Rotor Drive	4	1	2.3	0	0
2	20 -040-104-13	Pinion, Spiral Bevel, Tail Rotor Drive	10	1	5.8	0	0
3	204-040-108-7	Pinion, Planetary	284	12.5 *	12.2	0	0
4	204-040-132-1	Race, Bearing, Planetary Pinion	147	12.5 *	6.8	2	0.09
5	204-040-133-1	Retainer, Bearing, Planetary Pinion	41	4.5	[illegible].2	0	0
6	204-040-135-1	Bearing, Ball, Planetary Support and Accessory Drive	124	3	23.9	2	0.38
7	204-040-142-1	Bearing, Ball, Freewheeling	107	2	30.9	0	0
8	204-040-143-1	Bearing, Duplex, Ball, Tail Rotor Drive	52	4	7.5	2	0.29
9	204-040-190-7	Race, Inner, Freewheeling	9	1	5.2	5	2.89
10	204-040-191-7	Race, Outer, Freewheeling	6	1	3.5	0	0
11	204-040-250-9	Sleeve Assembly, Offset, Tail Rotor Drive	1	1	0.6	0	0
12	204-040-269-3	Bearing, Roller, Input Pinion	15	1	8.7	0	0
13	204-040-270-3	Bearing, Roller, Lower Mast	10	1	5.8	0	0
14	204-040-271-3	Bearing, Roller, Input Gear Shaft	10	1	5.8	0	0
15	204-040-305-1	Sleeve Assembly, Tail Rotor Drive	3	2	0.9	0	0
16	204-040-310-1	Bearing, Roller, Tail Rotor Drive	15	3	2.9	1	0.19
17	204-040-313-1	Spacer, Tail Rotor Drive	3	1	1.7	0	0
18	204-040-324-5	Shaft, Main Input Gear	5	1	2.9	1	0.56
19	204-040-329-1	Gear, Lower Sun	23	1	13.3	0	0
20	204-040-330-1, -3 **	Gear, Upper Sun	83	1	48.0	57	32.95
21	204-040-331-5	Ring Gear Assembly, Planetary	9	1	5.2	3	1.74

Table B-1. (Continued)

Item No.	Part Number	Part Name	Quantity Replaced	Quantity Per Trans.	% Replacement	Quantity Primary Failures	% Primary Failures
22	204-040-339-5	Housing, Jet No. 2	1	1	0.6	0	0
23	204-040-345-7	Bearing, Duplex Ball, Input Gear Shaft	38	1	22.0	21	12.14
24	204-040-346-3	Bearing Triplex Ball, Input Pinion	59	1	34.1	38	21.97
25	204-040-353-23	Case Assembly, Main, Bevel Gear	3	1	1.7	1	0.58
26	204-040-354-9	Case Assembly, Support	4	1	2.3	0	0
27	204-040-355-1, -3	Case Assembly, Accessory and Tail Rotor Drive	4	1	2.9	0	0
28	204-040-356-1	Sleeve, Spiral Bevel, Input	1	1	0.6	0	0
29	204-040-359-1	Case, Top	29	1	16.8	0	0
30	204-040-360-3	Planetary Assembly, Upper	1	1	0.6	0	0
31	204-040-379-3	Quill Assembly, Generator Drive	1	1	0.6	0	0
32	204-040-386-1	Case, Support, Bevel Gear	10	1	5.8	0	0
33	204-040-397-1	Spider, Planetary	2	1	1.1	0	0
34	204-040-700-1	Pinion, Spiral Bevel, Input	7	1	4.0	1	0.58
35	204-040-701-3	Gear, Spiral Bevel, Input	7	1	4.0	3	1.74
36	204-040-725-1, -3	Roller, Pinion, Planetary	15	12.5 *	0.6	0	0
37	204-040-762-1	Pinion, Accessory and Tail Rotor Drive	5	1	2.9	0	0
38	204-040-763-1	Gear, Accessory and Tail Rotor Drive	7	1	4.0	0	0
39	204-040-789-1	Washer, Spacer, Planetary	2	4	0.3	2	0.33
40	GG1669 (Nichols)	Oil Pump	28	1	16.2	0	0
41	X-131720 (Borg-Warner)	Freewheeling Clutch	11	1	6.4	4	2.31

* Twenty-two transmissions were the 15-pinion configuration, and 151 were the 12-pinion configuration.
** Six were -1

Table B-2. CH-47 Failure Mode Distribution by Component Class

	Spalled	Brinelled	Corroded	Dented	Elongated	Fretted	Gouged	Bent	Cracked	Chipped	Distorted	Dis-colored	Mutilated
Bearings	1.03 0.99 2.65 2.00	0.67 0.11 0.17 6.53	4.50 1.54 3.26 3.34	0.75 0.88 3.06 2.03	- - - -	0.27 0.77 0.20 0.30	1.35 1.21 0.40 0.42	0.51 0.11 - -	- 0.11 0.02 0.09	- - - 0.03	0.43 0.44 0.20 0.12	- - - -	0.11 0.11 0.02 0.03
Gears	0.03 - 0.02 0.48	- - - 0.03	0.19 0.55 0.66 1.21	0.83 0.33 0.26 0.27	- - 0.05 -	0.31 1.10 2.34 1.79	0.47 - 0.11 0.63	- - 0.02 -	- 0.77 0.23 0.48	0.03 - 0.02 0.09	0.11 - 0.02 -	0.03 - - -	0.51 - - 0.06
Lube System	- - - 0.03	- - - -	0.11 0.22 0.34 0.15	0.03 0.44 0.05 -	- - - 0.03	0.07 0.11 - 0.03	0.31 0.33 0.11 0.03	0.07 0.33 0.17 0.12	0.19 0.99 0.17 0.97	0.07 0.11 0.05 -	0.27 0.11 0.28 0.18	- - 0.02 -	1.55 1.32 0.43 0.33
Retention and Mounting Hardware	- - 0.20 0.03	0.11 0.66 - 0.03	0.91 1.43 1.58 0.63	0.11 2.31 0.46 0.12	0.03 1.43 0.14 0.06	0.15 0.88 1.06 0.42	0.63 2.20 1.01 0.69	1.03 1.65 0.20 0.24	2.47 3.63 3.23 3.19	0.07 - 0.46 0.27	0.71 1.87 0.37 0.27	- - 0.11 -	1.03 1.32 1.21 0.55
Nonrotating Structure	- - - -	- - - -	0.23 - 0.17 0.79	0.03 0.11 0.02 -	- - - -	0.03 - - -	0.31 0.11 0.02 0.18	- 0.11 - 0.03	- - 0.02 0.33	0.07 - - -	- - - -	- - - -	- 0.02 0.02 -
Shafts	0.07 - - -	- - - 0.12	0.35 1.32 0.26 0.03	- 0.11 0.02 0.03	- - - -	0.07 0.88 0.02 0.66	0.15 0.11 0.05 0.03	- - - -	0.19 0.11 0.11 0.18	- - - -	- - - -	- - - -	- - - -
Clutches	- - - -	- - - -	0.11 - - 0.03	- - - -	- - - -	- - - -	0.03 - - -	0.07 - - -	0.03 - - 0.06	- - - -	- - - 0.06	- - - -	- - - -

NOTE: All values are expressed in percent.

LEGEND

E	C
F	A

E = Engine transmission
C = Combining transmission
F = Forward transmission
A = Aft transmission

Table B-2. (Continued)

	Nicked	Part Missing	Pulled	Stripped	Worn	Scored	Torn	Frosted	Seized	Scuffed	Impressions	Smeared	Sheared
Bearings	0.31 0.55	0.03 0.11	- -	- -	1.91 0.77	1.55 0.44	- -	- -	- -	- 0.11	- -	0.35 0.22	- -
	0.49 0.12	0.26 0.21	- -	- -	7.16 4.47	1.41 1.45	- -	0.75 0.09	0.08 0.06	0.23 0.51	- 0.30	0.31 0.15	- 0.03
Gears	0.07 0.11	- -	- -	- -	0.23 -	0.19 0.22	0.03 -	0.19 0.33	- -	0.79 1.76	0.35 -	- -	- -
	0.17 0.57	- -	- 0.03	- 0.03	1.87 2.95	0.05 0.66	- 0.06	- 0.15	- -	0.02 1.27	0.02 0.09	- 0.05	- -
Lube System	0.39 0.44	0.23 2.20	- 0.55	0.27 0.66	1.03 2.97	0.15 1.21	0.03 0.44	- -	0.03 1.10	0.15 0.22	- 0.11	0.03 -	- -
	0.08 0.03	0.40 0.39	- -	0.02 0.03	1.96 0.36	0.17 0.09	0.05 -	- -	0.17 0.69	- -	- -	0.02 -	- 0.03
Retention and Mounting Hardware	0.43 0.99	0.23 0.99	- 0.33	0.11 0.55	9.21 9.35	0.71 0.77	- 0.99	- -	- -	0.27 0.22	- 0.11	0.07 0.33	- -
	0.83 0.27	0.11 0.15	0.08 -	0.43 0.06	14.79 16.60	1.76 1.27	0.63 0.18	0.05 -	0.02 -	0.11 -	0.05 0.36	0.02 0.03	- -
Nonrotating Structure	0.11 -	- -	- -	- -	0.63 0.88	- -	- -	- -	- -	- -	0.51 -	- -	- -
	0.05 0.09	0.05 0.09	- 0.03	0.02 0.15	0.98 0.79	- 0.24	- -	- -	- -	- -	- 0.09	0.02 -	- -
Shafts	0.03 0.11	- -	- -	- -	4.03 1.87	0.47 -	0.03 -	0.07 -	- -	0.11 0.33	- -	7.74 -	0.03 -
	0.05 [illegible]	- -	- -	- -	0.31 0.48	0.02 0.18	- -	- -	- -	- -	- -	- -	- -
Clutches	- -	0.19 -	- -	- -	7.14 -	0.07 -	0.03 -	- -	- -	0.03 -	- -	- -	- -
	- -	- 0.21	- -	- -	- 0.57	- -	- -	- -	- -	- -	- -	- -	- -

NOTE: All values are expressed in percent.

LEGEND

E	C
F	A

E = Engine transmission
C = Combining transmission
F = Forward transmission
A = Aft transmission

Table B-3. Success of Navy Oil Analysis Program (45)

Equipment	Removals	HITs	Success (%)
Fixed Wing	123	94	76.5
Helicopters			
Engines			
T58 (H-1, H-2, H-3, H-46)	7	6	
T63 (H-6, H-58)	1	1	
T64 (H-53, H-56)	21	13	
Total	29	20	69.0
Transmissions			
H-3	0	0	
H-46	6	4	
H-53	3	1	
Total	9	5	55.5
Gearboxes			
H-1	2	2	
H-2	5	0	
H-3	2	0	
H-53	0	0	
Total	9	2	22.2

Table B-4. Air Force SOAP Success - 1973

Equipment	Number of Samples	Removals MISS	Removals HIT	Success %
ALL	1,440,492	53	1,258	96.0
FIXED	1,386,327	52	1,241	96.0
HELICOPTER*				
H1 ENG	14,072	0	0	
H1 XMSN	15,152	0	6	
H3 ENG	8,768	0	0	
H3 XMSN	4,188	0	2	
H34 XMSN	960	0	1	
H34 GB	517	0	2	
H43 ENG	958	0	0	
H43 XMSN	909	0	1	
H46 XMSN	722	0	0	
H47 ENG	141	0	0	
H47 XMSN	224	0	0	
H53 ENG	3,882	0	0	
H53 XMSN	1,486	1	0	
H53 GB	287	0	0	
H58 ENG	780	0	0	
H58 XMSN	772	0	2	
Total ENG	28,662	0	0	-
Total XMSN	24,545	1	15	93.3
Total GB	1,018	0	2	100
GRAND TOTAL	54,225	1	17	94.4

*Models H-6, 12, 13, 19, 21, 52, 54 and 55 included in Total only, no HITs or MISSs.

Table B-5. Summary of Fort Rucker Microscopy Data - CH-47C*

Component	Hours**	Magnetic Particles	Nonmagnetic Particles	Reason for Microscopy
A8-750 Comb Box	1094	70 µm chips	30 µm Bronze	Excessive axial play in fwd. output shaft
A11-1563 #2 Eng. Trans.	1184	None	30 µm + very fine	Excessive metal on mag. plug + screens
A11-1822 #2 Eng. Trans.	428	280 µm slivers + chips	130 µm Bronze	Excessive metal on screens
A11-2046 #1 Eng. Trans.	2173	90 µm + fine	45 µm Bronze	Cluth failed
A11-2137 #1 Eng. Trans.	2080	None	480 µm Bronze	Retainer failed on output shaft bearing
A11-2541 #2 Eng. Trans.	2345	35 µm	480 µm Bronze	Excessive metal in screens
A11-2577 #2 Eng. Trans.	749	95 µm + fine	540 µm	Excessive metal in screens
A11-2658 #2 Eng. Trans.	840	300 µm	540 µm Bronze	Excessive metal on magnetic plug

* These cover ONLY cases where microscopy turned a MISS into a HIT.

** Since New or Overhauled.

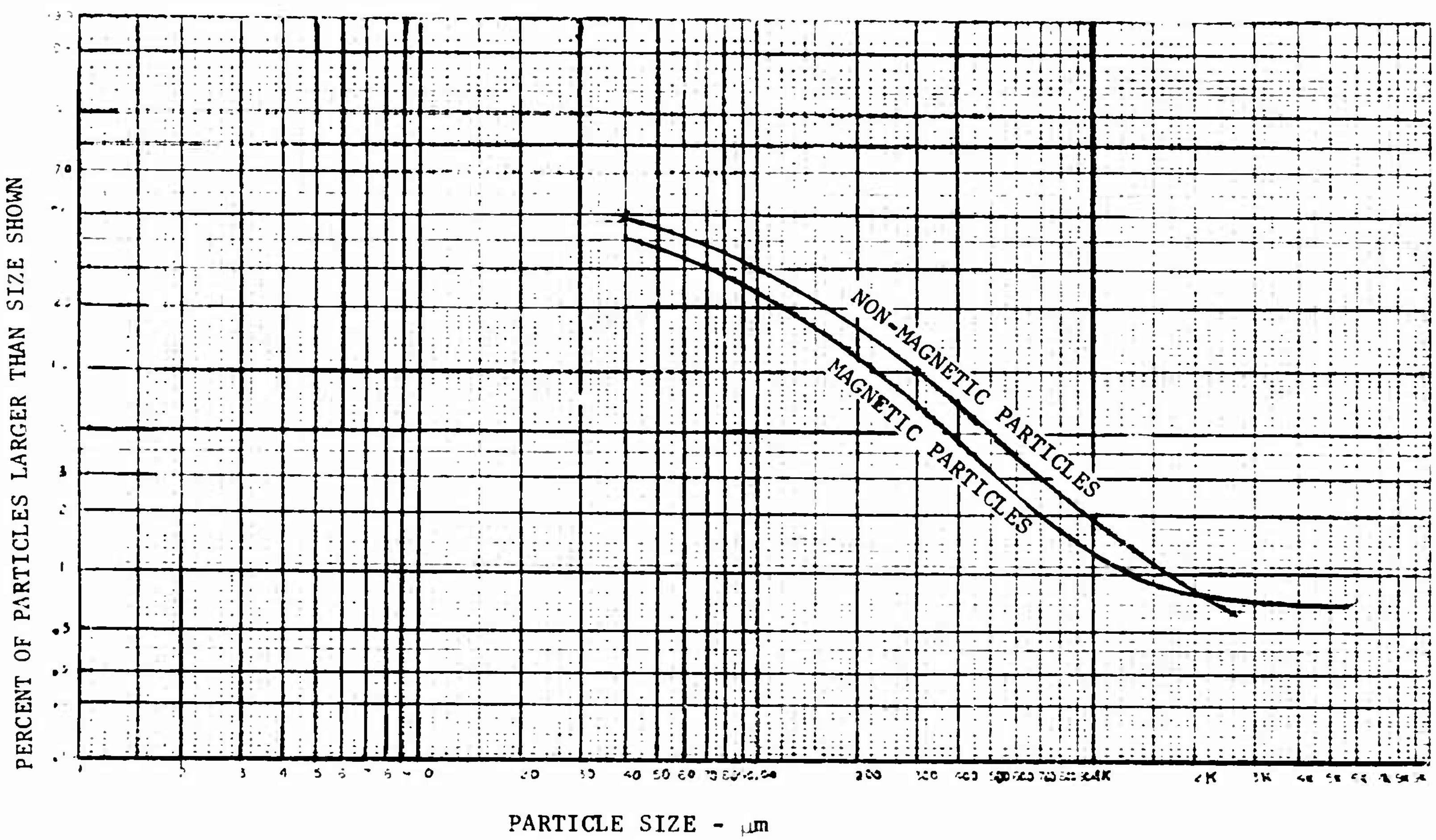


Figure B-1. Weibull Plot of Size of Chips From CH-47s at Fort Rucker.

Table B-6. Weibull Analysis of CH-47 Transmission Data

Serial No.	Position	Critical Parts	Hours**	Cumulative Failures	Censored Parts*	% Failed
A11-661	ENG	8	7	2	166	1.2
A7-596	FWD	14	14	4	154	2.6
A7-904	FWD	6	17	10	130	7.7
A11-484	ENG	8	21	12	124	9.7
A9-881	AFT	17	24	19	114	16.7
A8-631	COMB	8	28	23	110	20.9
A11-903	ENG	8	32	25	104	24.0
A11-1258	ENG	8	39	26	97	26.8
A7-859	FWD	6	42	27	92	29.3
A7-94	FWD	14	51	29	80	36.3
A9-791	AFT	17	55	39	73	53.4
A11-1539	ENG	8	63	40	60	66.7
A11-1307	ENG	8	97	41	53	77.4
A7-688	FWD	6	108	43	49	87.8
A7-807	FWD	6	141	46	46	99+

* Surviving out of 172.

** Operated after first ASOAP indication.

APPENDIX C

METALS USED IN UH-1 AND CH-47 COMPONENTS

In spite of the low value placed on laboratory diagnosis in the main body of this report, the ASOAP work could be strenghtened by better knowledge of helicopter metallurgy. One benefit could be simply detection of improperly labeled samples. A more subtle benefit could be avoidance or postponement of costly removals when the laboratory can ascertain that some noncritical part is wearing. However, this would require a great deal of skill, and would not be possible at all in many ambiguous cases.

By way of illustration, Table C-1 shows the metals for the 20 parts most likely to fail in the UH-1 transmission. (The oil pump and clutch subassemblies are too complex to include, though they had replacement rates of 16.2% and 6.4% respectively.) The first three columns are from Bowen (26), the next two columns are from a compilation by Barron (54), and the remainder from standard metals handbooks. The "Figure No." citations are from TM55-1520-210-55P.

It is evident that a report of silver (Ag) would be specific for Part No. 200-040-271-3, and would justify prompt removal since roller bearings go very rapidly. However, there are no other unambiguous cases, and the evaluator would have to depend on such reasonings as "Nickel (Ni) means gear wear, and gears have more forgiveness than bearings. But, gear wear particles shorten the life of bearings, unless the filtration is exceptionally good." The evaluator will tend to the safety first viewpoint, so that any plan for reducing costs through laboratory diagnosis is apt to prove disappointing.

Tables C-2 through C-5 show similar data for the four transmissions on the CH-47C. The data were obtained from the Boeing Vertol Company, as discussed in Appendix B. While less teardowns were available than on the UH-1, these data tell a similar story.

It would be quite easy to compile similar lists for the engines and gearboxes, and the entire CH-54 and UTTAS aircraft, if the ASOAP Laboratory Chiefs feel these lists are sufficiently useful.

Table C-1. Metals in UH-1 Transmission

Part No. 200-040-	Part Name	%(1) Replaced	Figure No.	Alloy(2)	Fe	Al	Cu	Cr	Mg	Mn	Mo	Ni	Ag	Sn	V	Zn
					Metals Present											
330-1/3	Gear, Upper Sun	48.0	145-29	6260	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0
346-3	Bearing, Triplex Ball, Input Pinion	34.1	157-21	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
				+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
142-1	Bearing,Ball, Freewheeling	30.9	157-4	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
				+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
135-1	Bearing, Ball, Planetary Support (Acc. Drive)	23.9	145-20 145-27	52100 + Phenolic	97	0	0	1.5	0	0.4	0	0	0	0	0	0
345-7	Bearing, Duplex Ball, Input Gear Shaft	22.0	157-4	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
				+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
359-1	Case, Top	16.8	1'5-8	AZ91C	0	9.0	0	0	90	0.2	0	0	0	0	0	0.7
329-1	Gear, Lower Sun	13.3	148-4	6260	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0
108-7	Pinion, Planetary	12.2	147-4	6260	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0
269-3	Bearing, Roller, Input Pinion	8.7	149-20	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
				+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
143-1	Bearing, Duplex Ball, Tail Rotor Drive	7.5	162-20	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
				+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
132-1	Race, Bearing, Planetary Pinion	6.8	148-5	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
104-13	Pinion, Spiral Bevel, Tail Rotor Drive	5.8	162-23	6260	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0
270-3	Bearing, Roller, Lower Mast	5.8	137-6	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
				+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
271-3	Bearing, Roller, Input Gear Shaft	5.8	149-36	6490	90	0	0	4.0	0	0	4.3	0	(3)	0	1.0	0
				+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
386-1	Case, Support, Bevel Gear	5.8	145-46	AZ91C	0	9.0	0	0	90	0.2	0	0	0	0	0	0.7
190-7	Race, Inner, Freewheeling	5.2	157-9	6260	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0

Table C-1 (Continued)

Part No. 200-040-	Part Name	% Replaced [1]	Figure No.	Alloy [2]	Metals Present: Fe	Al	Cu	Cr	Mg	Mn	Mo	Ni	Ag	Sn	V	Zn
331-5	Ring Gear Assembly, Planetary	5.2	147-8	4140	98	0	0	1.0	0	0.9	0.2	0	0	0	0	0
700-1	Pinion, Spiral Bevel, Input	4.0	157-32	6260	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0
701-3	Gear, Spiral Bevel, Input	4.0	150-19	6260	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0
763-3	Gear, Acc. and Tail Rotor Drive	4.0	149-5	6260	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0

(1) Based on 173 transmission overhauls.

(2) 6260 = AMS designation for AISI 9310 Steel.
6490 = AMS designation for M50 tool Steel.

(3) Plating.

Table C-2. Metals in CH-47C Forward Transmission

Part No. 114-	Part Name	%[1] Replaced	Alloy[2]	Metals Present											
				Fe	Al	Cu	Cr	Mg	Mn	Mo	Ni	Ag	Sn	V	Zn
DS 281	Bearing	100	6490	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0
			+ 9310	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0
DS 250	Bearing	43	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
D 2184	Retainer	28	2014[3]	1.0	91	4.5	0.1	0.5	0.8	0	0	0	0	0	0.3
DS 161	Bearing	11	6490	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0
DS 282	Bearing	9	6490	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0
			+ 9310	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0
D 1245	Rotor Shaft	4	9310	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	0	0

(1) Based on 47 transmission overhauls.

(2) 6490 = AMS designation for M50 tool steel.

(3) Plus 0.15% Ti.

Table C-3. Metals in CH-47C Aft Transmission.

Part No. 114-	Part Name	% Replaced (1)	Alloy (2)	Metals Present: Fe	Al	Cu	Cr	Mg	Mn	Mo	Ni	Ag	Sn	V	Zn
DS 281	Bearing	100	6490	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0
DS 282	Bearing	71	6490	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0
DS 240	Bearing	35	6490+	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0
			52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0.3
D 2184	Retainer	29	2014	1.0	91	4.5	0.1	0.5	0.8	0	0	0	0	0	0.3
D 2167	Housing	29	AZ91C	0	9.0	0	0	90	0.2	0	0	0	0	0	0.7
DS 284	Bearing	24	6490	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0

(1) Based on 17 transmission overhauls.

(2) 6490 = AMS designation for M50 tool steel.

(3) Plus 0.15% Ti.

Table C-4. Metals in CH-47C Combining Transmission

Part No. 114-	Part Name	%[1] Replaced	Alloy[2]	Metals Present											
				Fe	Al	Cu	Cr	Mg	Mn	Mo	Ni	Ag	Sn	V	Zn
D 5243	Support Assembly	78	AZ91C	0	9.0	0	0	90	0.2	0	0	0	0	0	0.7
DS 571	Bearing	11	6490	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0
			+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
DS 667	Bearing	11	6490	90	0	0	4.0	0	0	4.3	0	0	0	1.0	0
			+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
D 5240	Housing	11	AZ91C	0	9.0	0	0	90	0.2	0	0	0	0	0	0.7

(1) Based on 18 transmission overhauls.

(2) 6490 = AMS designation for M50 tool steel.

Table C-5. Metals in CH-47C Engine Transmission.

Part No. 114-	Part Name	% Replaced	Alloy	Metals Present Fe	Al	Cu	Cr	Mg	Mn	Mo	Ni	Ag	Sn	V	Zn
D 6244	Pinion Gear	92	9310	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	1.0	0
D 6250	Retainer, Spiral Bevel Gear	38	AZ91C	0	9.0	0	0	90	0.2	0	0	0	0	0	0.7
D 6241	Housing	34	AZ91C	0	9.0	0	0	90	0.2	0	0	0	0	0	0.7
D 6262	Oil Baffle	28	6061	0	98	0.3	0.3	1.0	0	0	0	0	0	0	0
D 6252	Oil Baffle	20	6061	0	90	0.3	0.3	1.0	0	0	0	0	0	0	0
D 6266	Shaft	16	9310	94	0	0.3	1.2	0	0.6	0.1	3.3	0	0	1.0	0
DS 662	Bearing	16	52100	97	0	0	1.5	0	0.4	0	0	0	0	0	0
			+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0
DS 668	Bearing	14	6490	97	0	0	1.5	0	0.4	0	0	0	0	0	0
			+ Bronze	0	0	95	0	0	0	0	0	0	5	0	0

APPENDIX D

DETAILS OF PROGNOSIS HARDWARE

This appendix displays examples of prognosis hardware in most of the classes discussed in Section 5. No display of a spectrometer or microscope is made, as these are well-known. The nucleonic detector is not displayed since it is quite new. The shock pulse meter is adequately described in Section 5.8. One leading example of each of the other devices is included for the reader's information. Inclusion does not constitute endorsement by the author or contractor, nor does exclusion indicate that another brand is considered inferior. The addresses of the suppliers are shown in Table D-1.

1. Wear Debris System

An advanced magnetic chip collector is shown in Figures D-1 and D-2. The first of the two sketches gives an overall view of a Wear Debris System, consisting of the sensor (permanently installed in the transmission), and a small, hand-held, battery-operated box with cable and plug for the purpose of "interrogating" the sensor. The second sketch shows the sensor plug itself, with its self-closing valve permitting visual inspection of the collected debris without oil drainage or spillage.

2. Chip Collector

The debris monitor utilizes a sensing grid woven in a unique pattern. Transparent polyester filaments which serve as insulators are interwoven with stainless steel conductors. These elements are locked together with a third small-diameter, stainless-steel wire which also greatly improves the contact surface when debris is impinged on the grid by the oil flow. Conductors are electrically interconnected to provide multiple indicating zones. These zones can be made sensitive to various quantities of particles such as initial particle collection, warning, and alarm. By selecting zones large enough, nuisance indications can be eliminated. However, the sensor still provides early warning of mechanical deterioration due to its fast response. Rate of accumulation can also be determined by monitoring the time between indications. It is this information that truly indicates impending component failure and allows an operator to intelligently determine how much longer the equipment should remain in use.

Figure D-3 shows a typical sensor configuration. Lubricating oil flows axially through the open end and is deflected through the sensing grid by the solid cone secured to the screen at the downstream end. As debris collects along the interface of the screen, the flow will gradually divert itself to the remaining open area and thus randomly distribute the debris over the entire area of the sensor. Any debris that is electrically conductive (both ferrous and nonferrous) will be detected. By the addition of a differential pressure switch across the screen similar to that used on full flow filters, the total accumulation of conductive and nonconductive debris can be indicated.

Table D-1. Suppliers

Item	Manufacturer and Address
Wear Debris System	Technical Development Company 24 East Glenolden Ave., Glenolden, Pa. 19036
Chip Collector	K West 9371 Kramer Ave., Westminster, Ca. 92683
Light Scattering Meter	Environment One Corporation 2773 Balltown Rd, Schenectady, N.Y. 12309
Particle Counter	Pacific Scientific Company 4619 West Brooks St., Montclair, Ca. 91763
DR Ferrograph	Trans-Sonics, Incorporated P.O. Box 326, Lexington, Ma. 02173

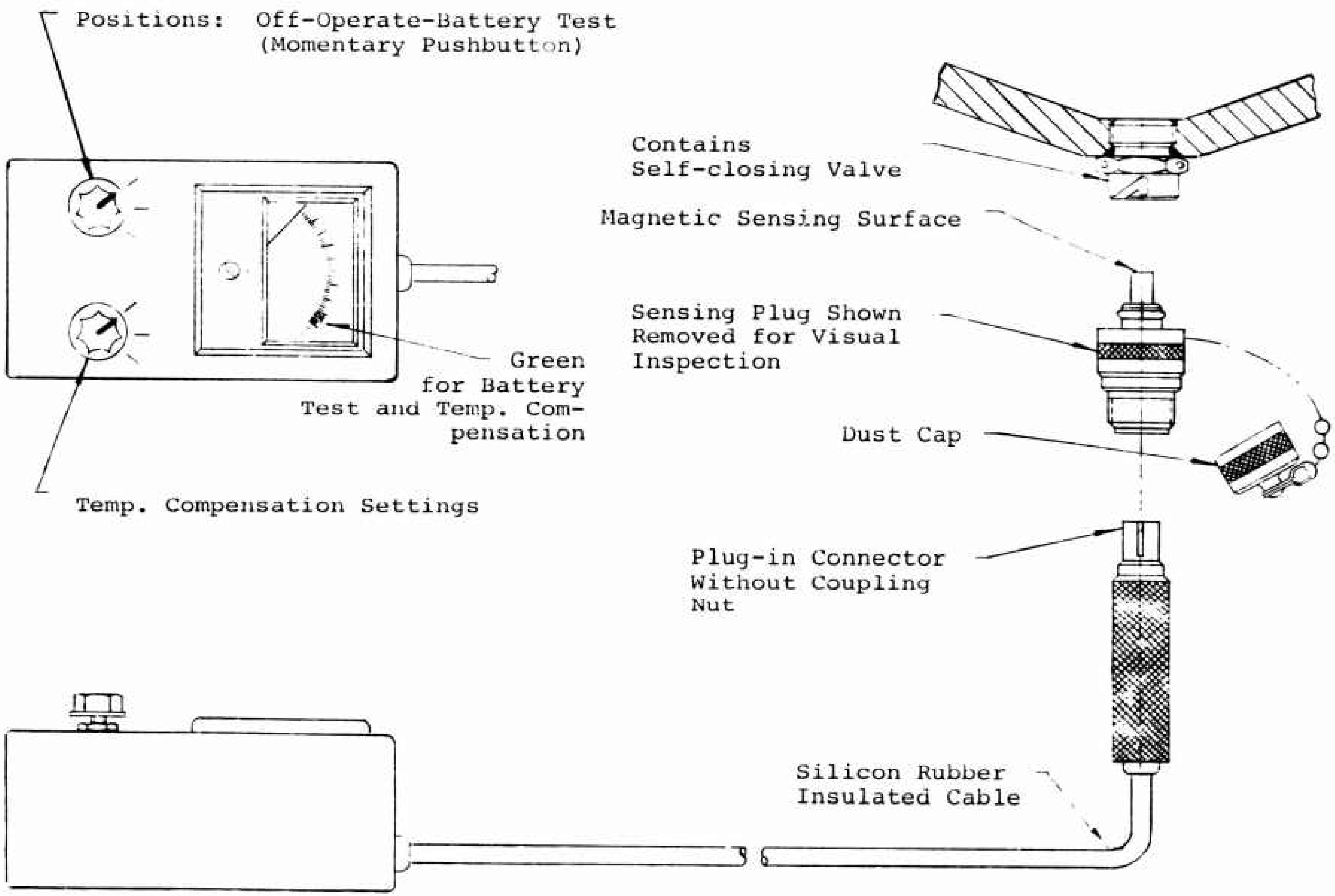


Figure D-1. Tedeco Portable Wear Debris System.

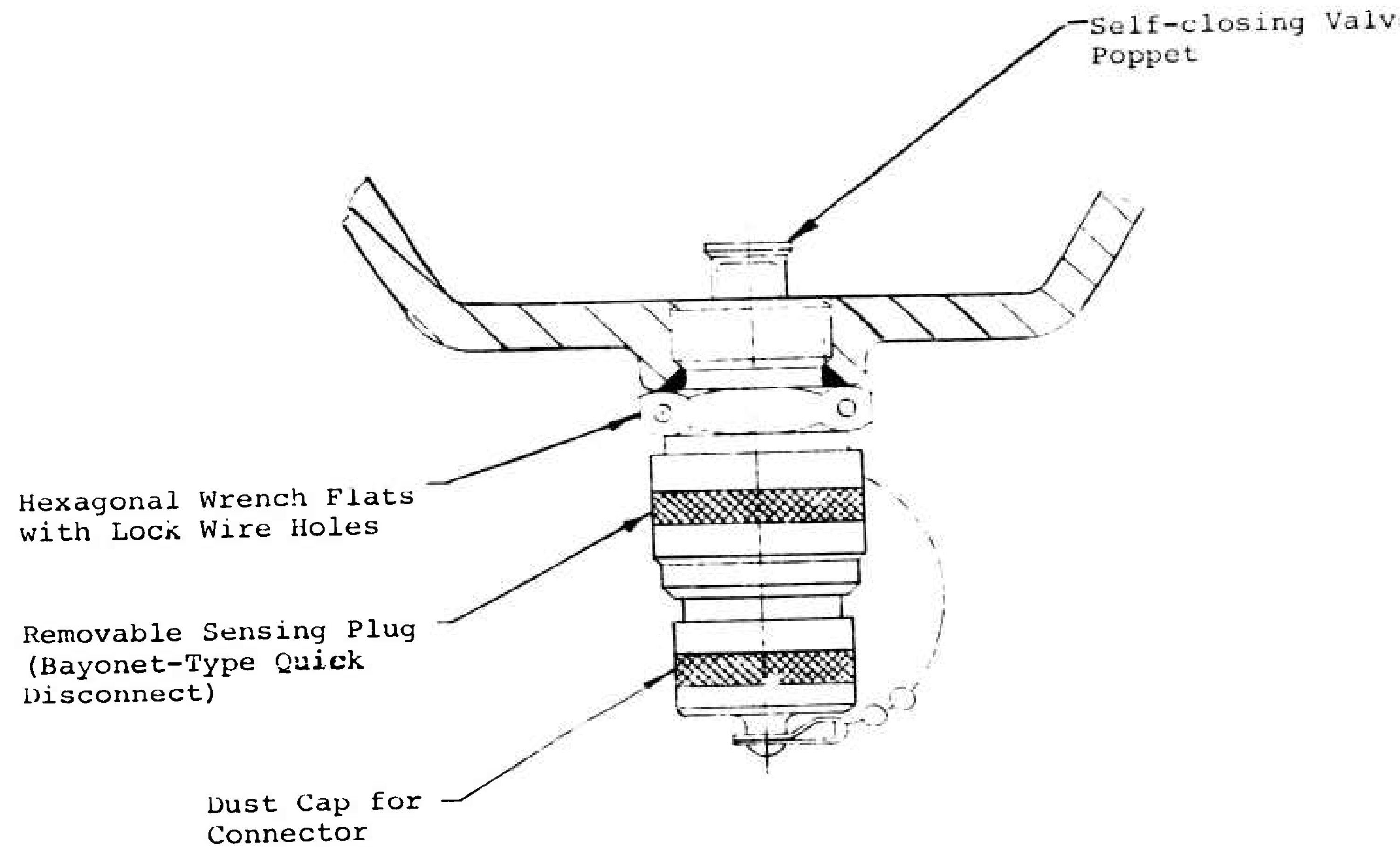


Figure D-2. Tedeco Magnetic Wear Debris Sensor with Self-Closing Valve.

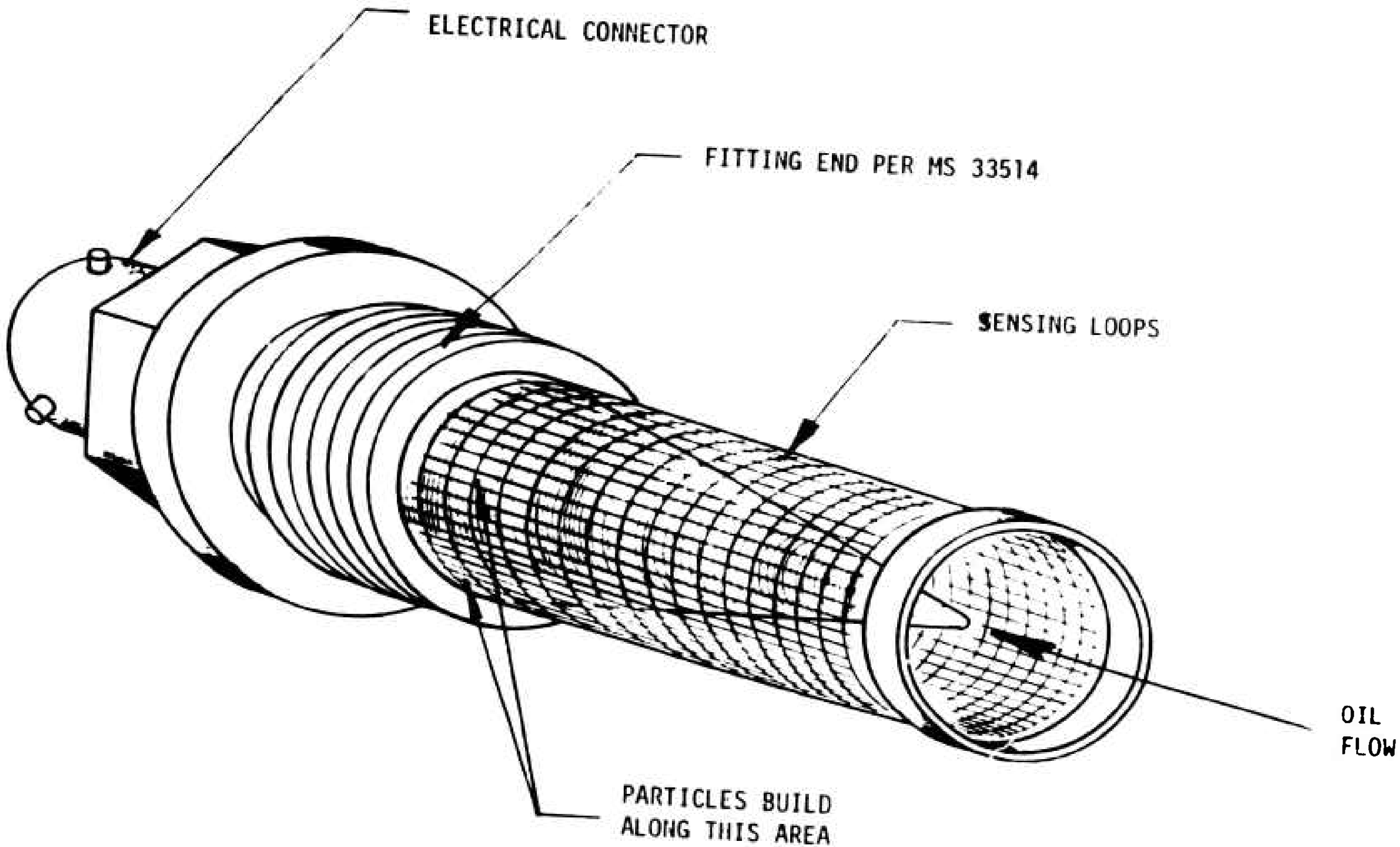


Figure D-3. Sensor Configuration.

Figure D-4 shows a typical configuration of the sensor and a tee housing. Other units employ the screen straight across the flow. Sensor shapes are usually determined by effective area for a given pressure drop, mesh size, flow rate, and available location.

3. Light Scattering Meter

The design approach of the static oil monitor is shown in Figure D-5. Two solid-state light sources are energized alternately. One source provides a reference beam which, together with fixed optical scattering and reference elements, produces light signals in the scattering and attenuation photo-sensors. The other light source projects a beam through the oil, which produces scattering and attenuation signals in the same photo-sensors. The scattering photo sensor, therefore, receives light pulses which alternate between those resulting from light scattered from particles in the oil, and from the fixed scattering reference. The attenuation photo sensor similarly receives pulses which alternate between those resulting from oil attenuation and the attenuation reference.

The signal conditioner circuits use the reference pulses to compensate for photo sensor gain variations and changes in light transmission due to deposits on the fiber optics. This arrangement also compensates the scattering reading for changes in light levels due to oil attenuation. System stability depends upon the relative outputs of the light sources. Over 1000 hours of testing of a similar system at elevated temperatures has shown that this can be accomplished if the light sources are maintained at the same temperature, and energized by equal current pulses.

Specifications

The system specifications are as follows:

Oil Type: Jet engine synthetic lubricant

Operating Temperature: Oil to 350°F; ambient temperature at light sources limited to 200°F

Operating Pressure: 85 psi

Outputs: Scattering channel - full scale (5 volts DC) corresponds to 20 ppm aluminum
Attenuation channel - full scale (5 volts DC) corresponds to zero light through one-inch oil path length

Oil Flow Rate: Zero to any practical maximum by use of by-pass

Vibration: Transducer (hard mounted) to 2000 Hz, .05 inch peak-to-peak, or 50 g's whichever is less
Signal conditioner - 15 g's maximum (may be shock mounted)

Power: 28 V DC, approximately 8 watts

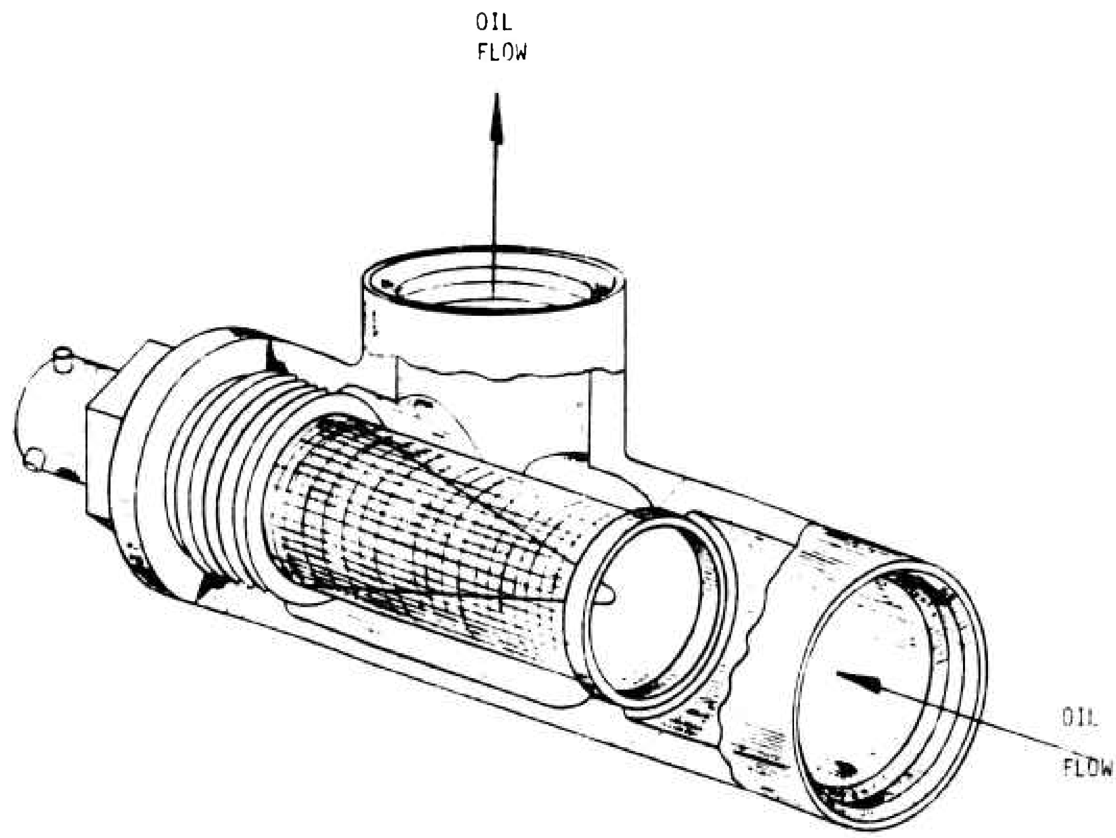
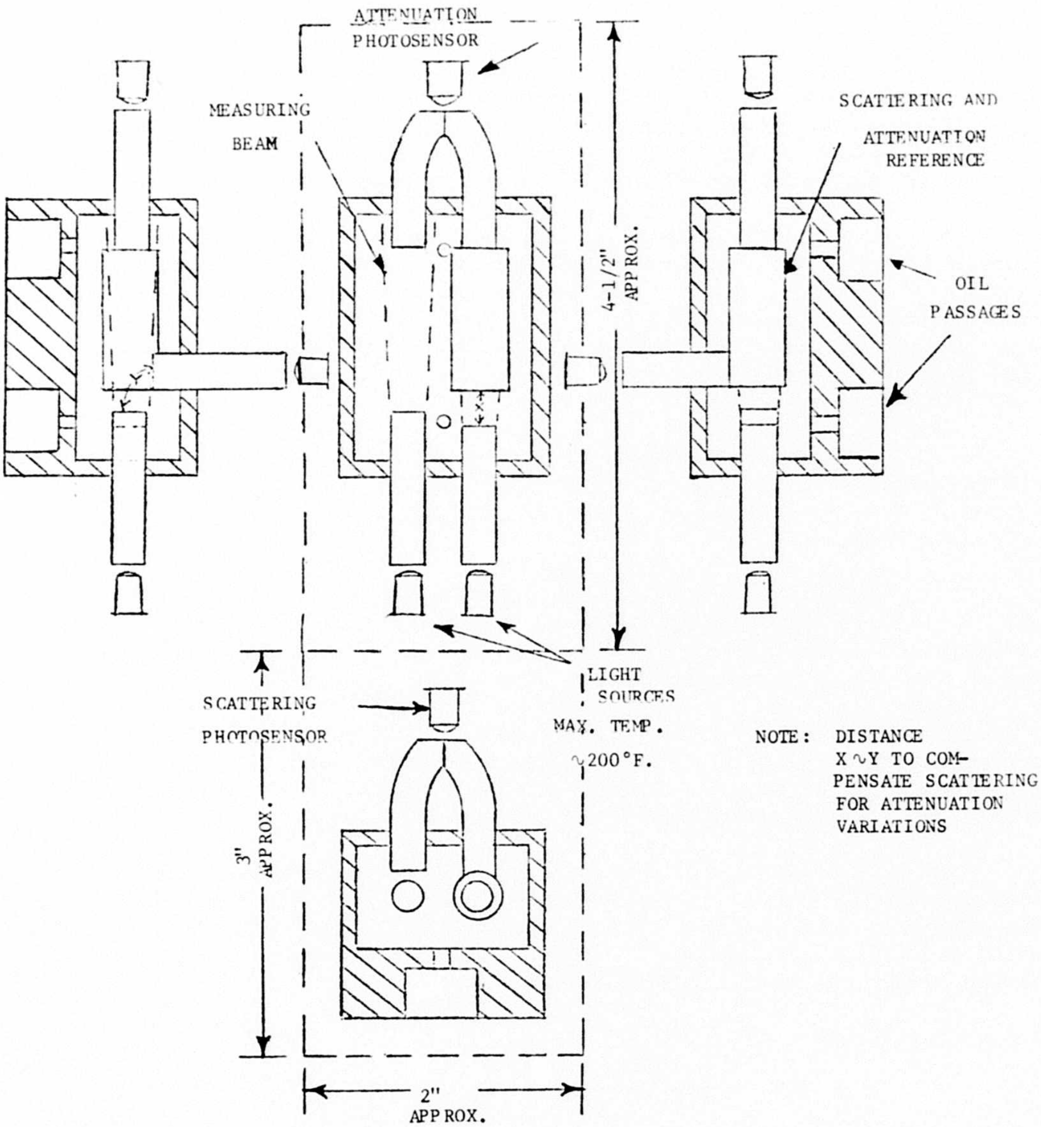


Figure D-4. Sensor and Tee Housing.



ESTIMATED DIMENSIONS: 2" x 3" x 5"
ESTIMATED WEIGHT: APPROX. 2 LB

NOTE: Dimensions and weight are approximate; do not include connectors or special fittings, etc.; also do not include encapsulation for higher temp. use (above 200°F)

Figure D-5. Static In-Line Oil Monitor.

4. Particle Counter

Sample fluid flows through a small rectangular fluid passage and past a window as shown in Figure D-6. Particles in the fluid pass by the window one by one (as long as specified limits of concentration are not exceeded). Light from a tungsten lamp is formed by the window to a parallel beam of an exact size and directed onto a photodetector.

The automatic lamp adjust circuit establishes the proper base voltage from the photodetector. Each particle, as it passes the window, interrupts a portion of the light beam according to its size. This causes a specific reduction (or pulse) in the voltage which is proportional to the size of the particle. Two counting circuits (channels) with preset thresholds tally the particles by size. A size range adjustment is provided for each channel generator.

The system is designed to perform automatic analyses of contamination in samples of oil from military helicopters. Referring to the block schematic diagram (Figure D-7), the oil in its sample bottle is placed in the sample holder.

Pushing the "START" button pressurizes the enclosure, forcing the sample fluid to flow through the sensor at a constant rate. Each particle in the fluid gives rise to a pulse at the output of the sensor, the size of the pulse being proportional to the size of the particle.

The stream of pulses is sorted and counted in the PC-220; those correspondong to particles smaller than 5 μm being counted in Channel "A", while those larger than 5 μm are counted in Channel "B". Each channel can accumulate a maximum of 999,999 counts.

Parallel BCD data corresponding to the two six-digit totals are available at the output of the PC-220. They are fed into the microprocessor and processed in accordance with the program shown in Figure D-7, after which the totals A&B, along with the ratio B/A, are printed out on a ticket having spaces for sample identification, etc.

5. DR Ferrograph

Figure D-8, a diagram of the optical system of the Type 7067 DR Ferrograph, illustrates the basic principles of operation. Oil is mixed with a proprietary developer and siphoned from a small bottle. The function of the developer is to promote precipitation of the particles and to help in stabilizing the viscosity of the oil. The DR Ferrograph uses gravity feed, and the oil flows through an expendable precipitator tube on which the magnetic particles are deposited.

The particles grade as to size along the length of the magnet, with the largest particles deposited at the entry end and the smallest near the exit. A trifurcated fiber optic bundle conducts light from a single lamp and passes equal intensity beams through the tube at three selected

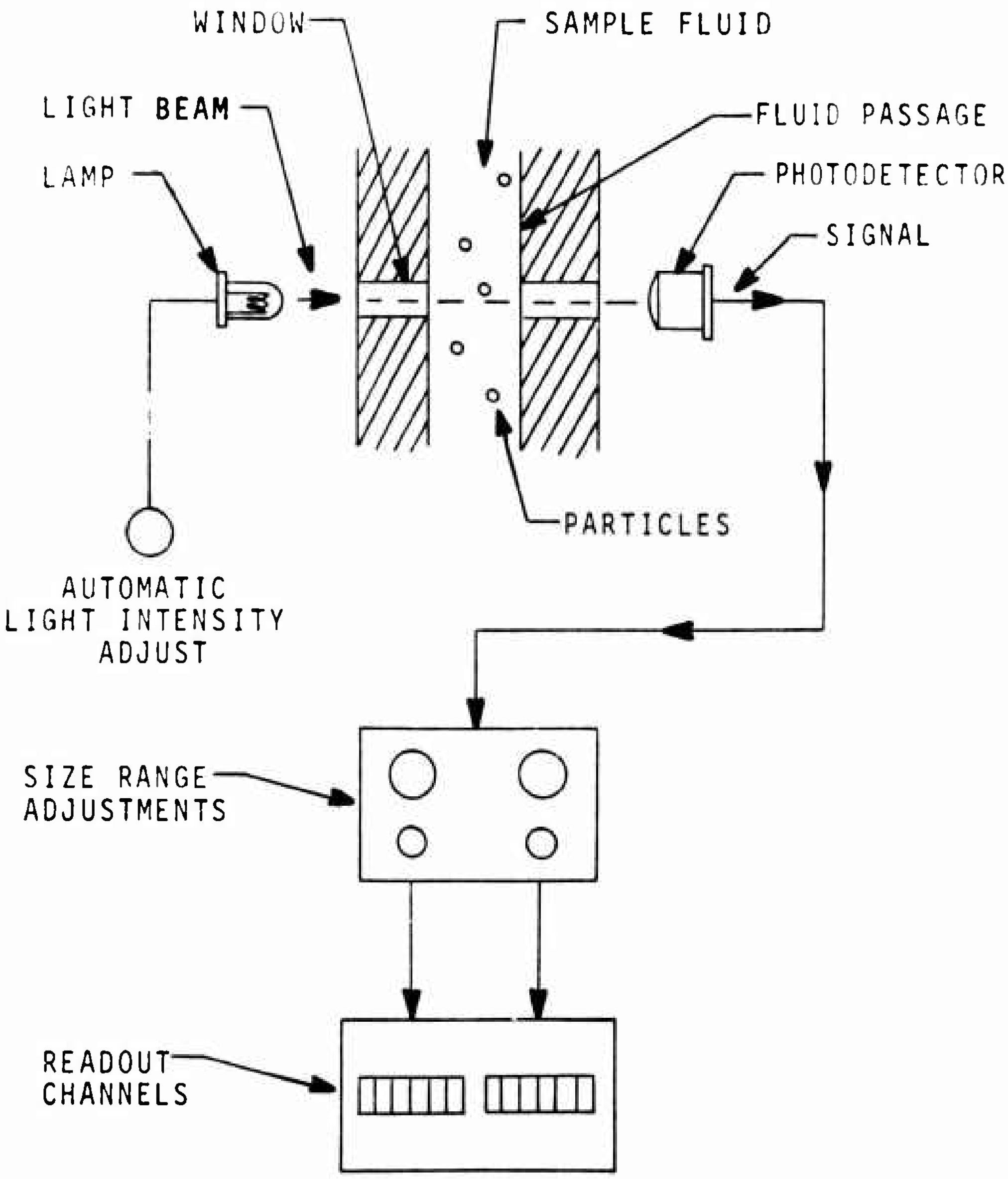


Figure D-6. Principles of HIAC Particle Counter.

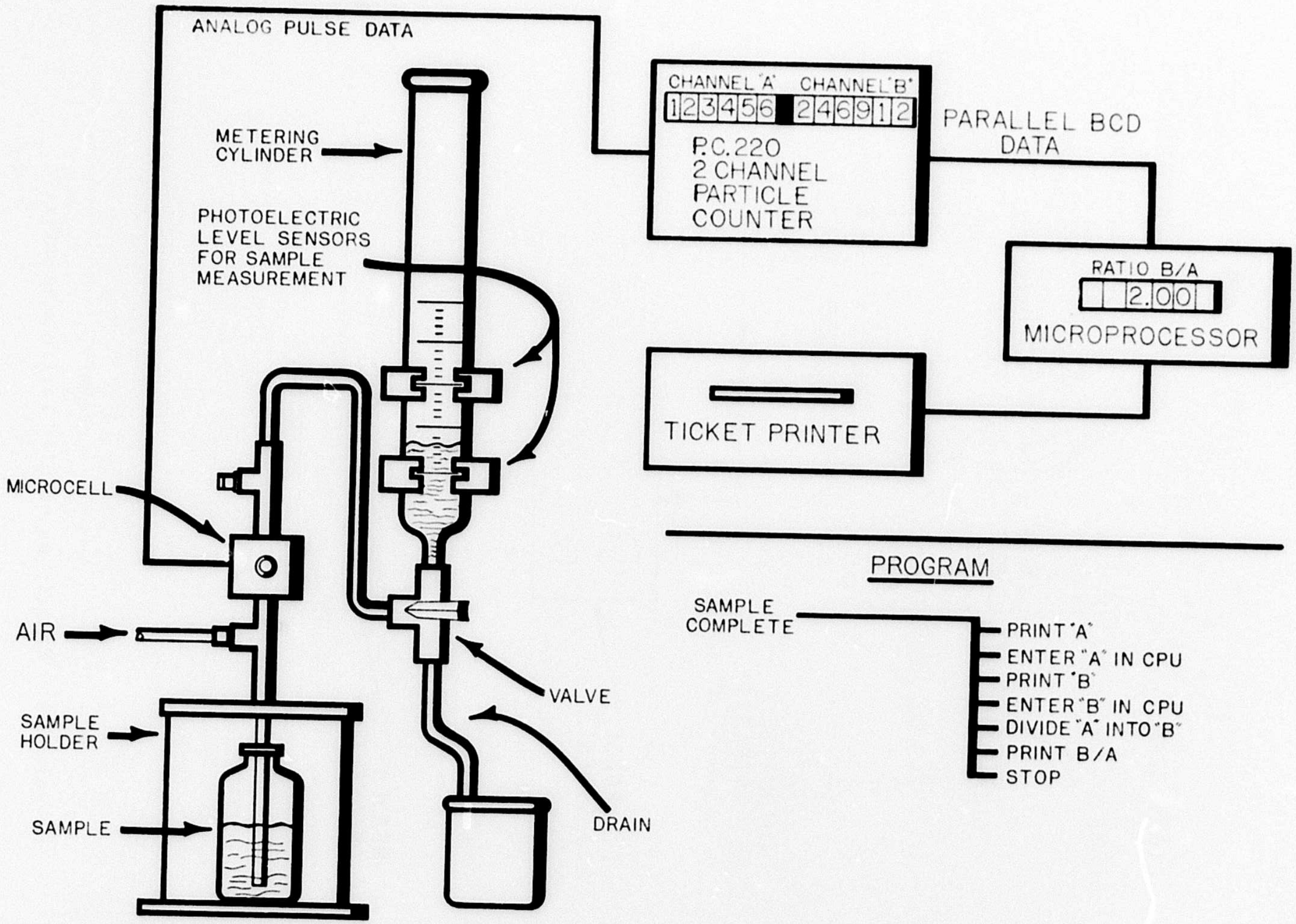


Figure D-7. Block Schematic of Automatic Sample Analyzer.

locations. One of the locations is outside of the magnetic field and is a reference. The light that passes through this reference bundle is used to actuate a photodetector which in turn controls an amplifier that supplies power to the light source. The light intensity received by the reference photodetector is maintained constant. In this way, the light intensity crossing a clear portion of the tube remains constant, independent of oil color.

Light from the same lamp is passed across the tube at two separate locations. One location is the place where steel particles of approximately 5 μm size and larger are deposited. The other location is the place where steel particles of approximately 1 to 3 μm are deposited. The digital reading is proportional to the percentage of the area covered by opaque particles.

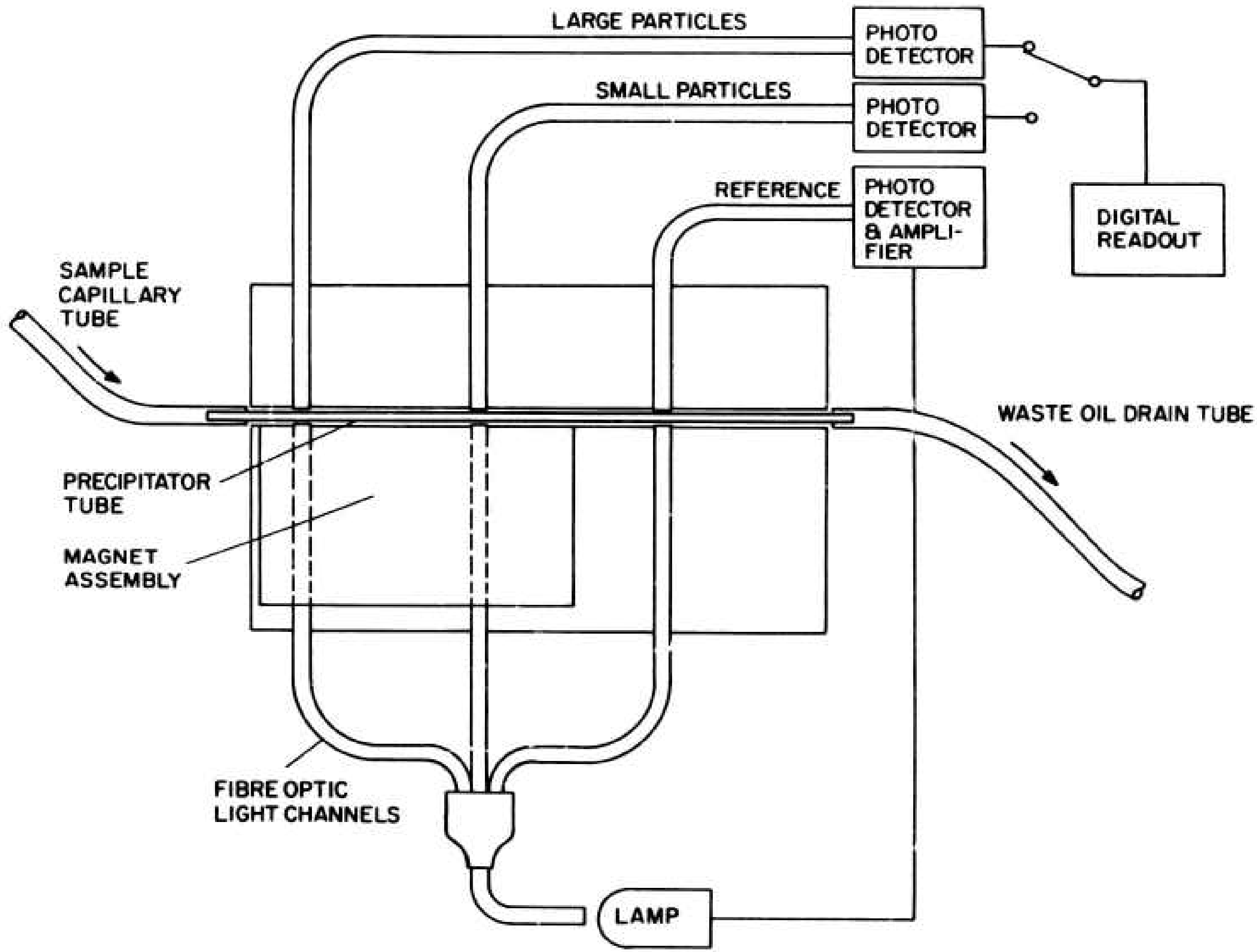


Figure D-8. Optical System of Type 7067 DR Ferrograph.

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